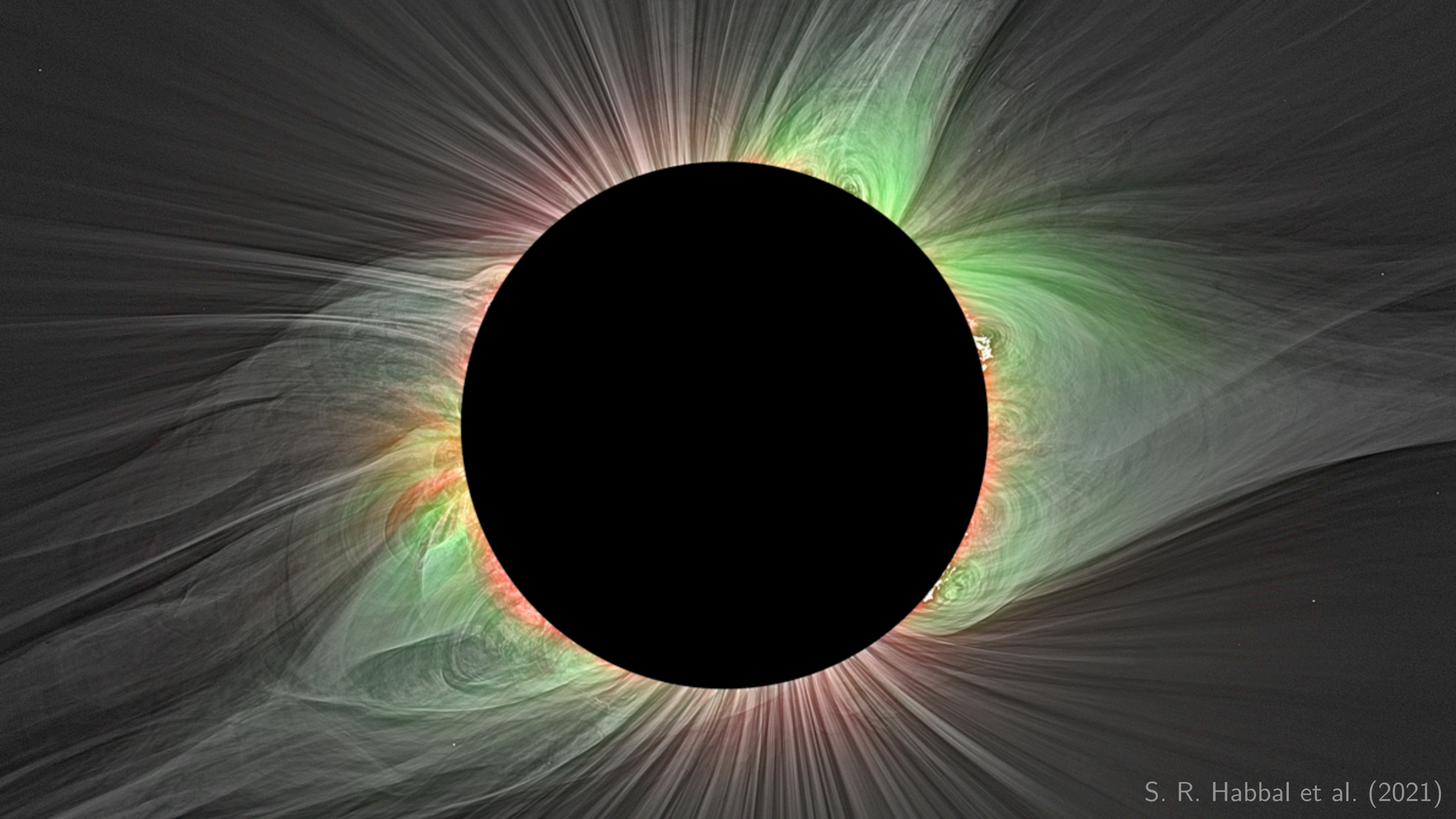
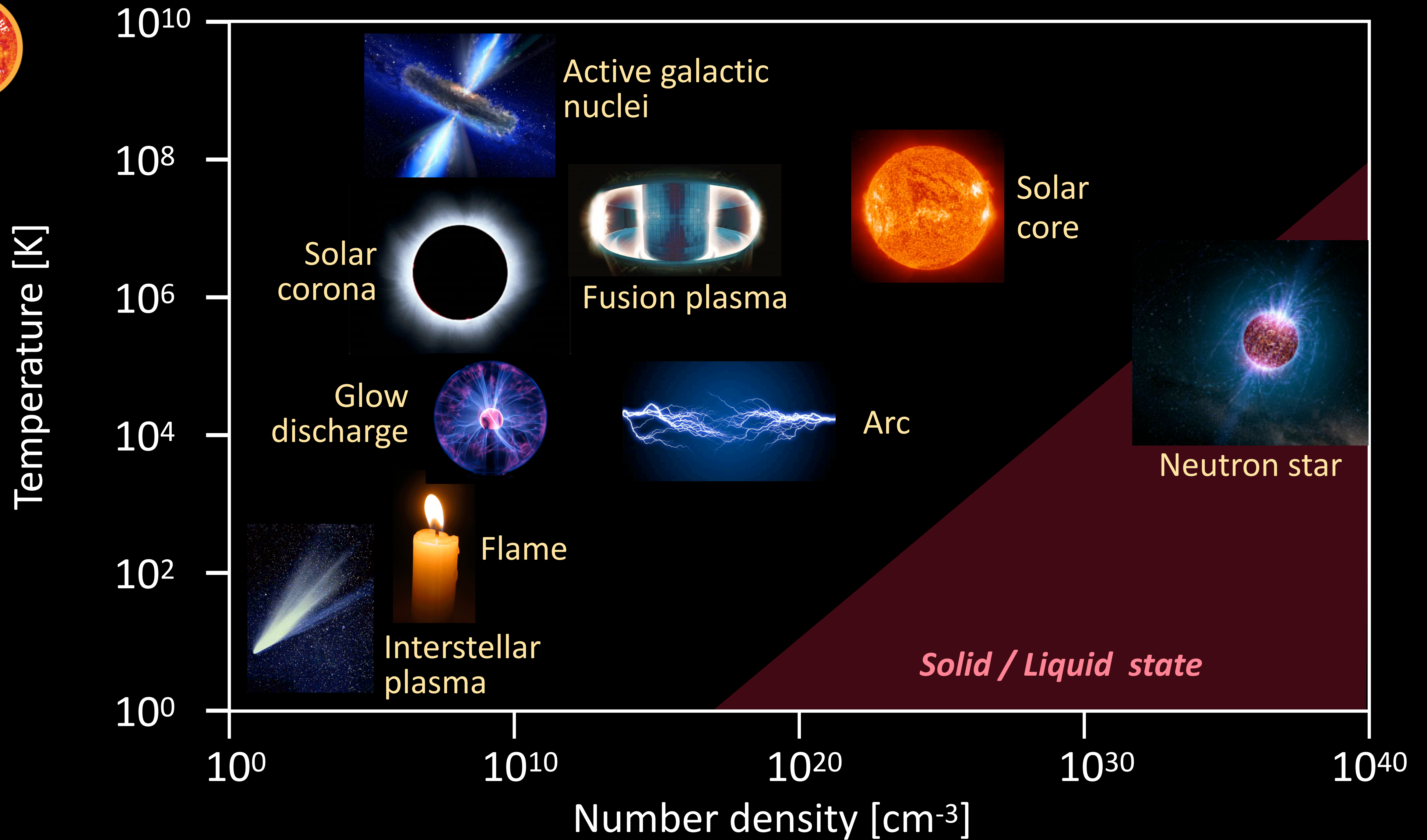


# Un rêve devenu réalité : pénétrer dans une atmosphère stellaire, celle du Soleil









# Unsolved problems in contemporary physics

- Is there a theory which explains the values of all fundamental physical constants ?
- Why does time have a direction?
- Baryon asymmetry: Why is there far more matter than antimatter in the observable universe?
- Hierarchy problem: Why is gravity such a weak force?
- What is the identity of dark matter?
- Is it possible to make a theoretical model to describe the statistics of a turbulent flow ?
- Why is the solar corona so much hotter than the solar surface?
- ...

*Wikipedia (July 2023)*





# Unsolved problems in contemporary physics

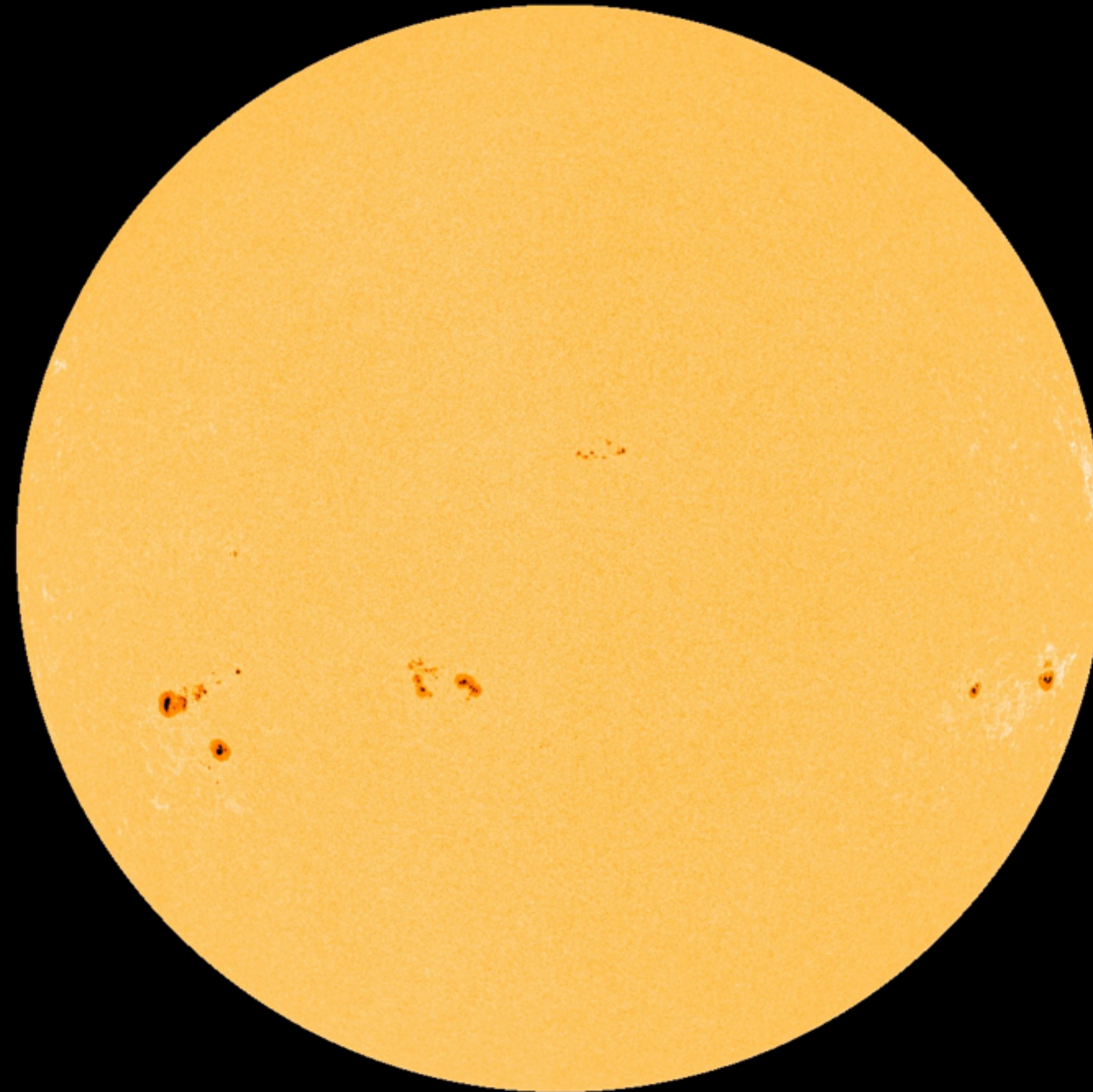
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*Wikipedia (July 2023)*





# The Sun in visible light

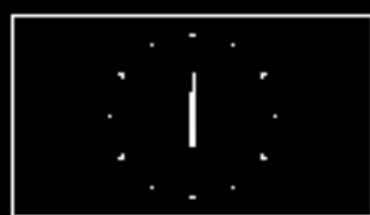
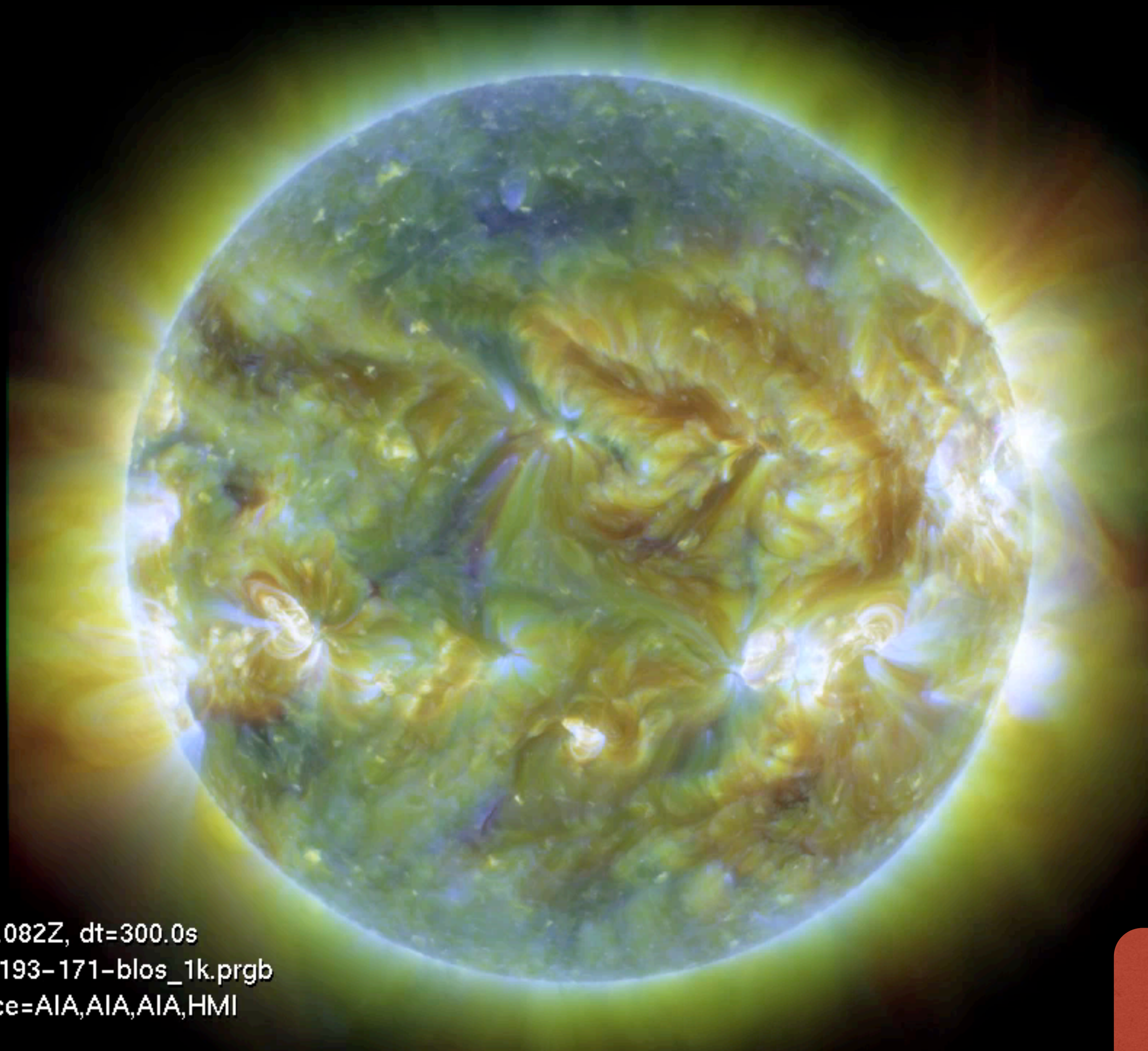


SDO/HMI Quick-Look Continuum: 20131029\_163000

surface temperature  
5772 °K



# The Sun in extreme UV (17-21 nm)

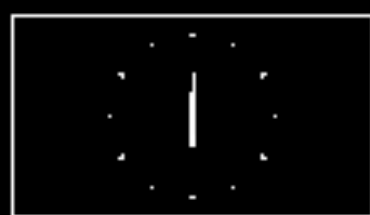
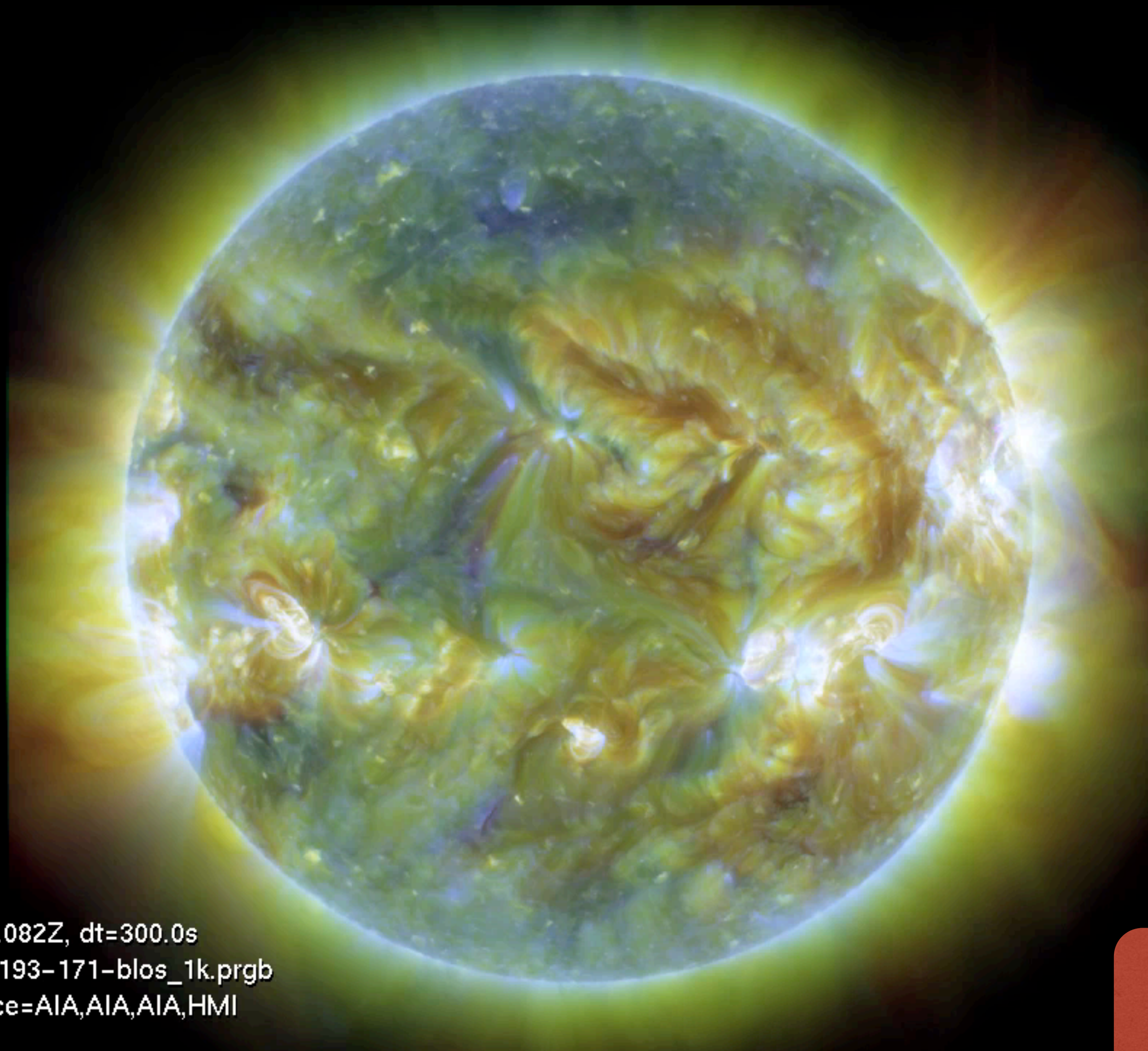


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channel=211, 193, 171, source=AIA,AIA,AIA,HMI

**coronal temperature  
> 10<sup>6</sup> °K**



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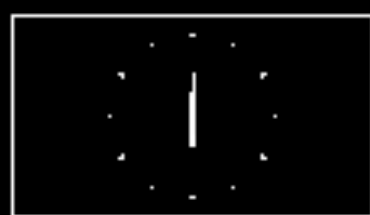
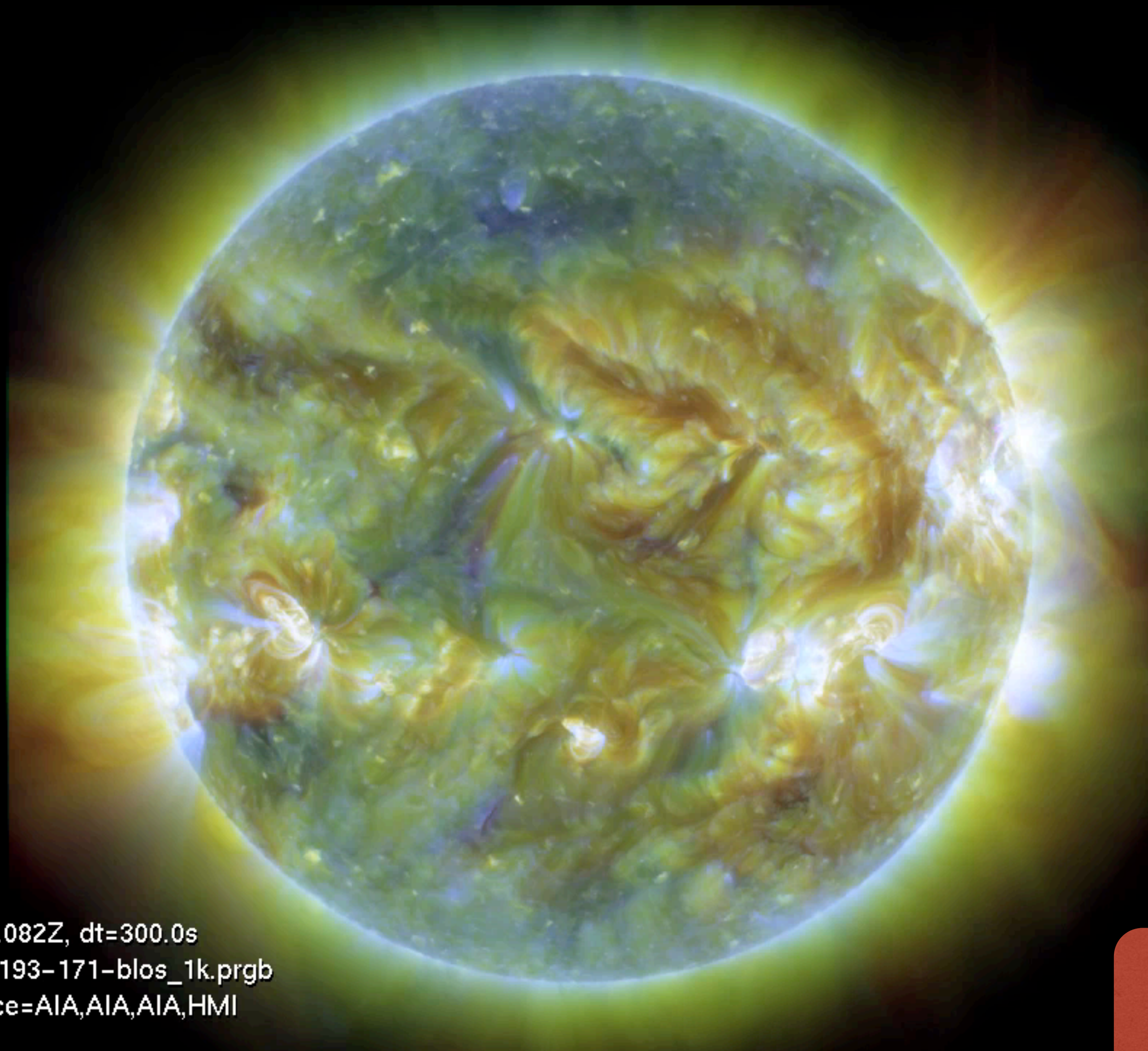
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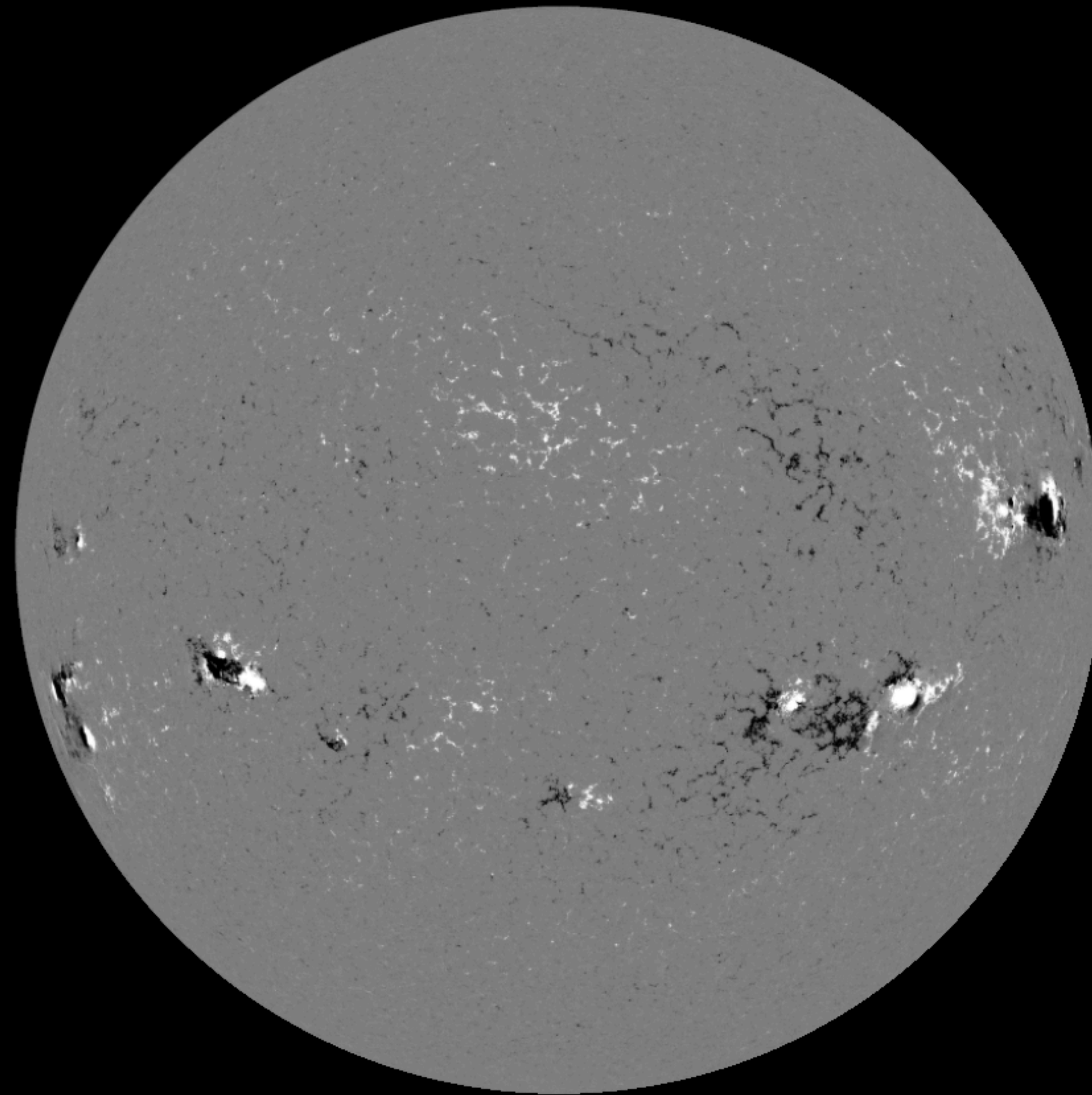


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aia\_20131027T180007\_211-193-171-blos\_1k.prgb  
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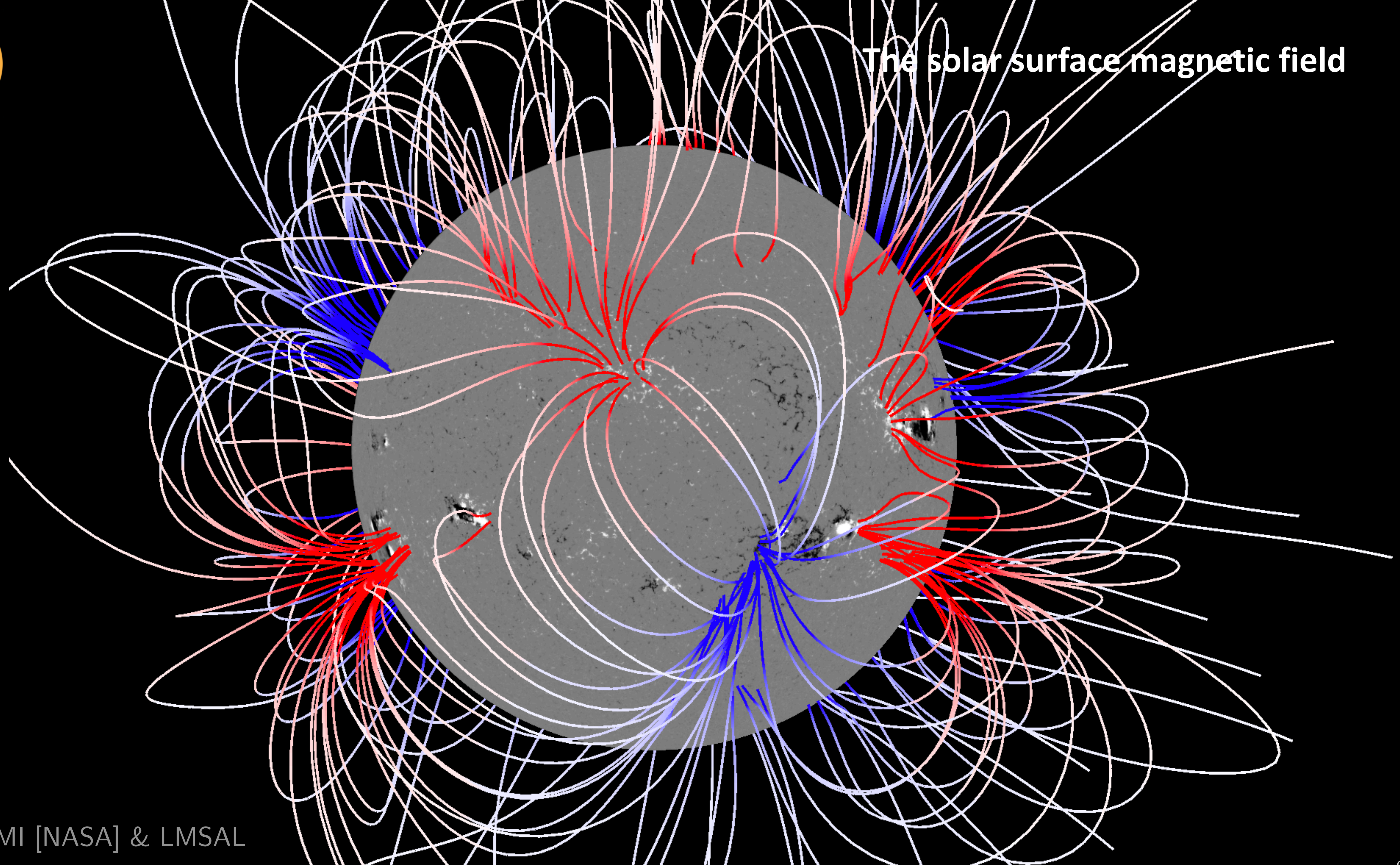


# The solar surface magnetic field



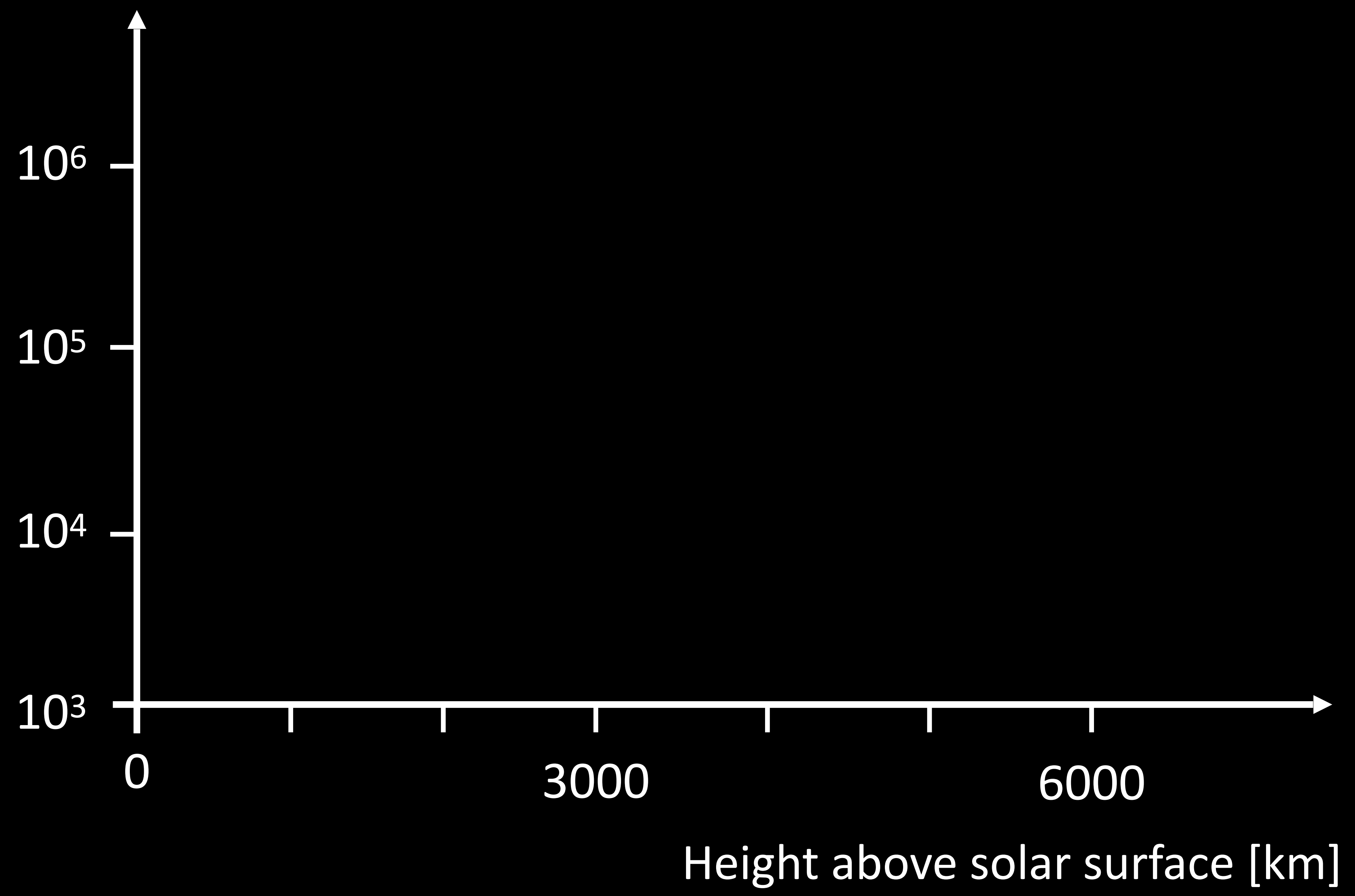


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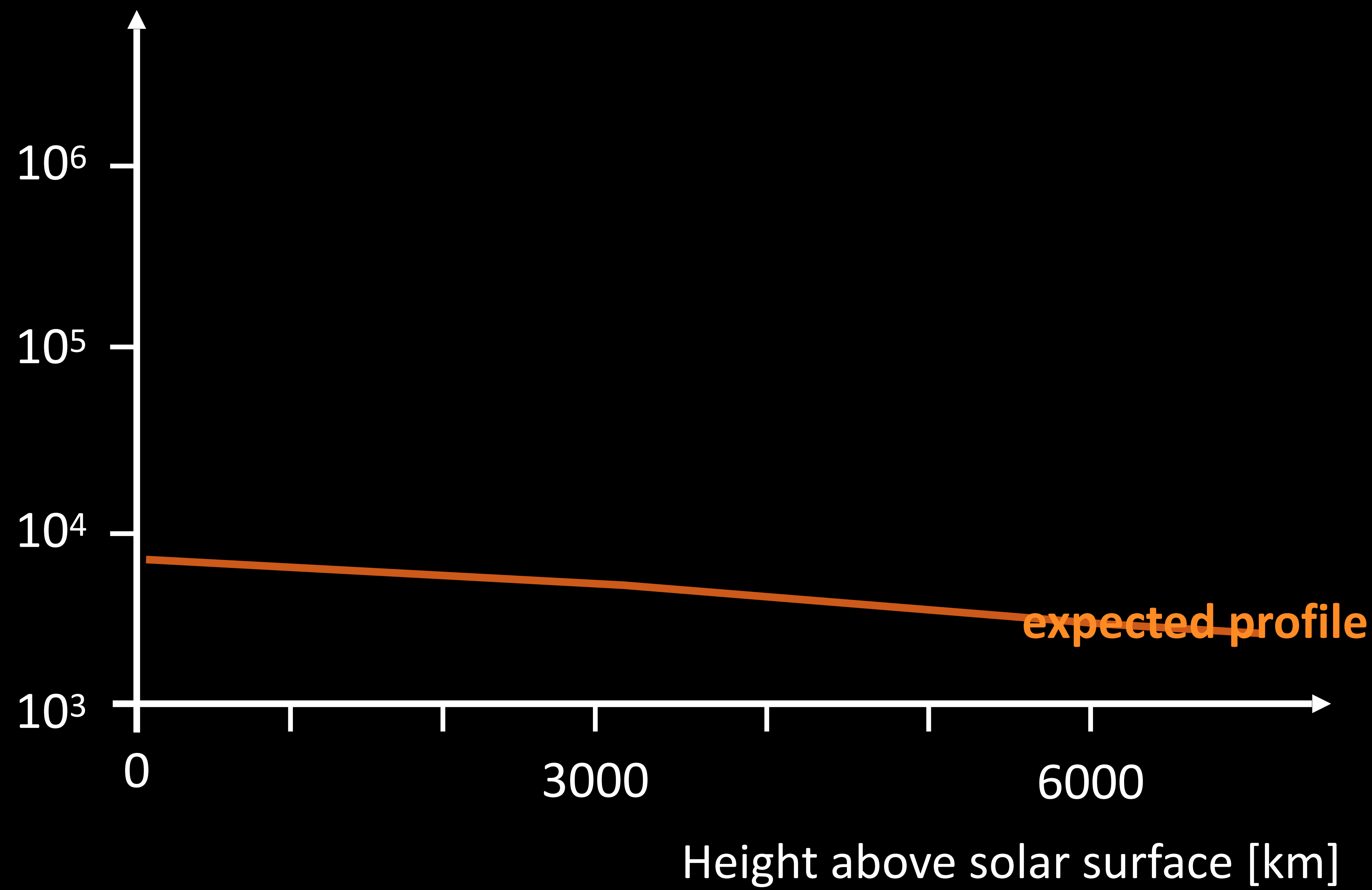


# Electron Temperature [K]



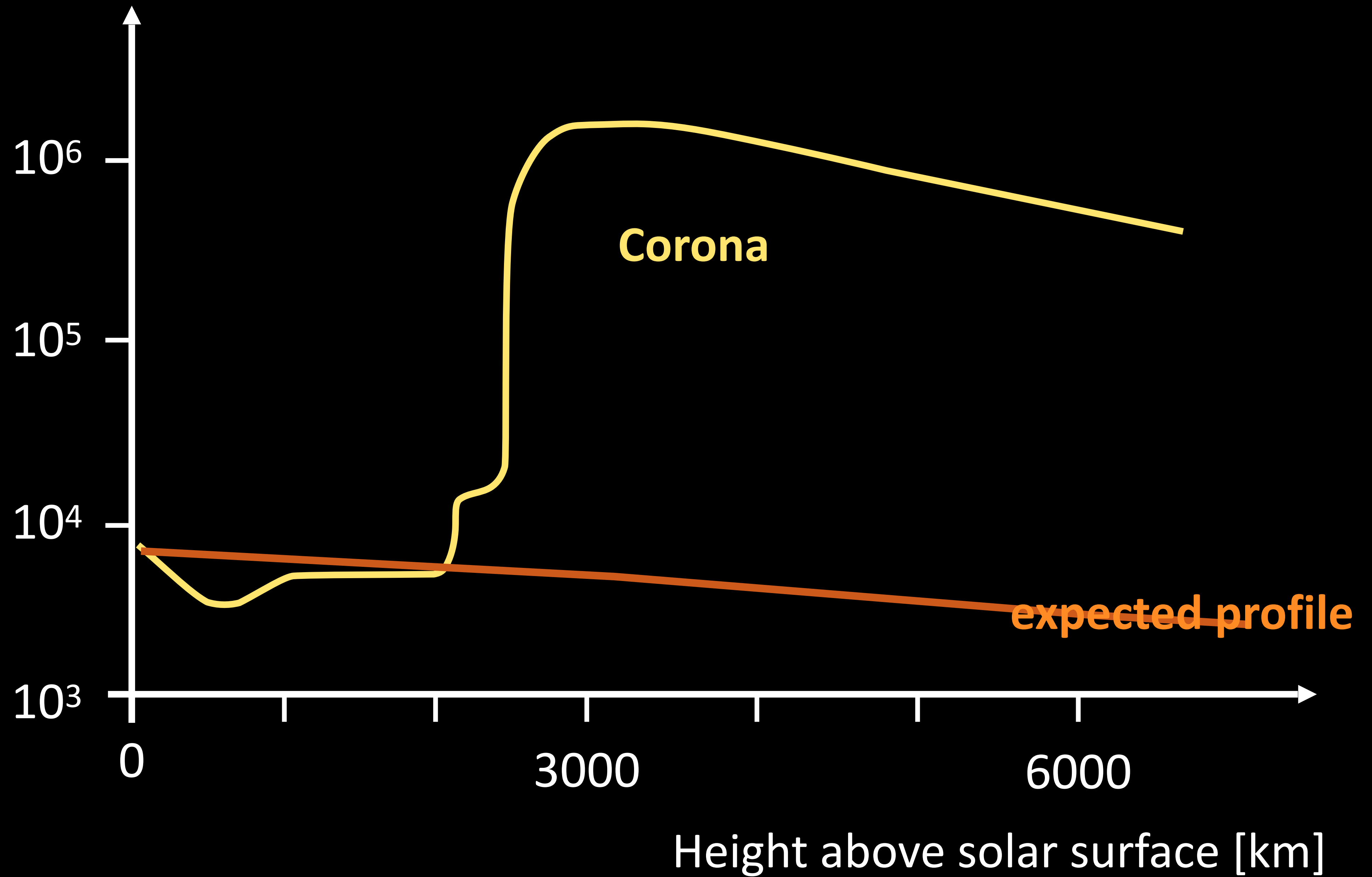


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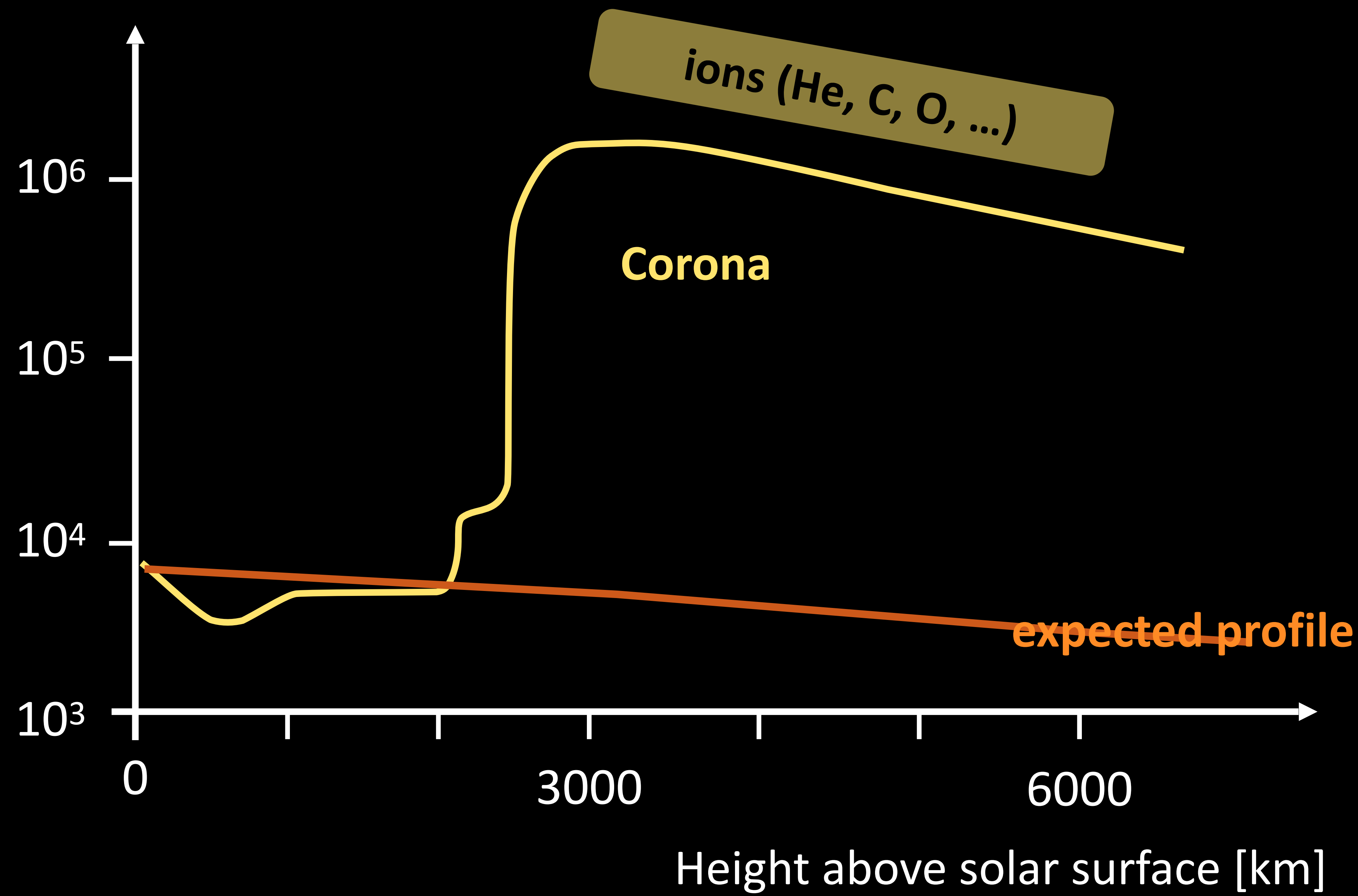


# Electron Temperature [K]





# Electron Temperature [K]





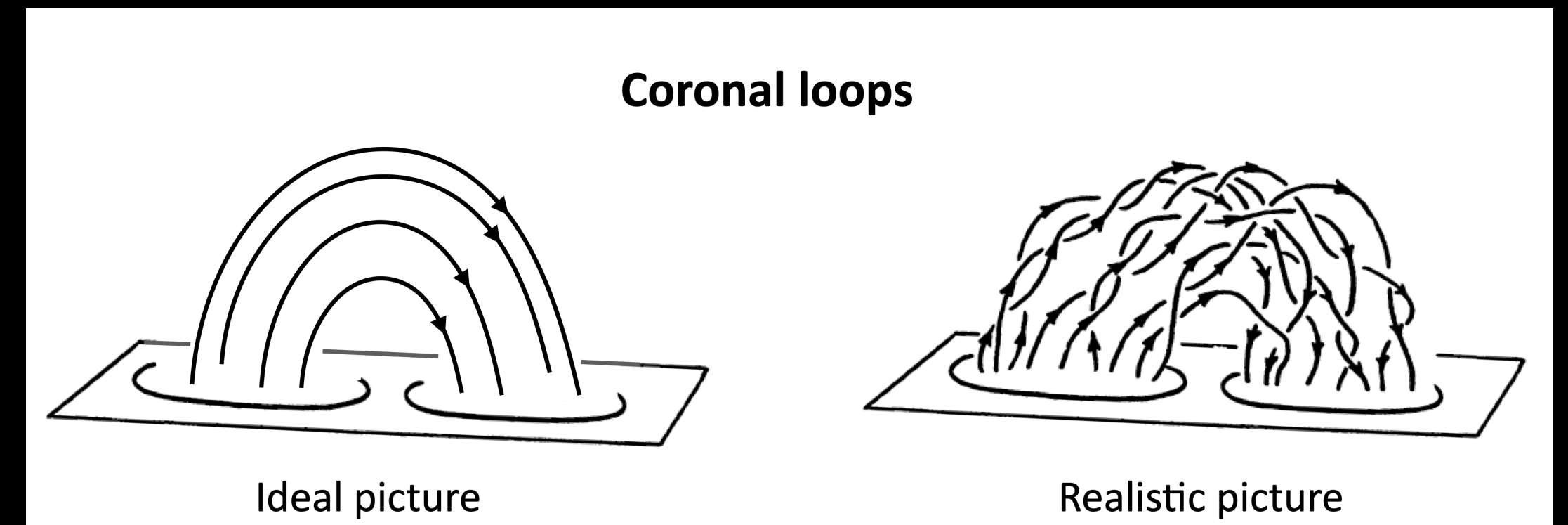
# What we know

Main energy reservoir : turbulent motion inside the Sun

→ drives the complex topology of the magnetic field

→ magnetic energy gets transported to higher altitudes

→ magnetic energy is irreversibly converted into thermal/kinetic energy

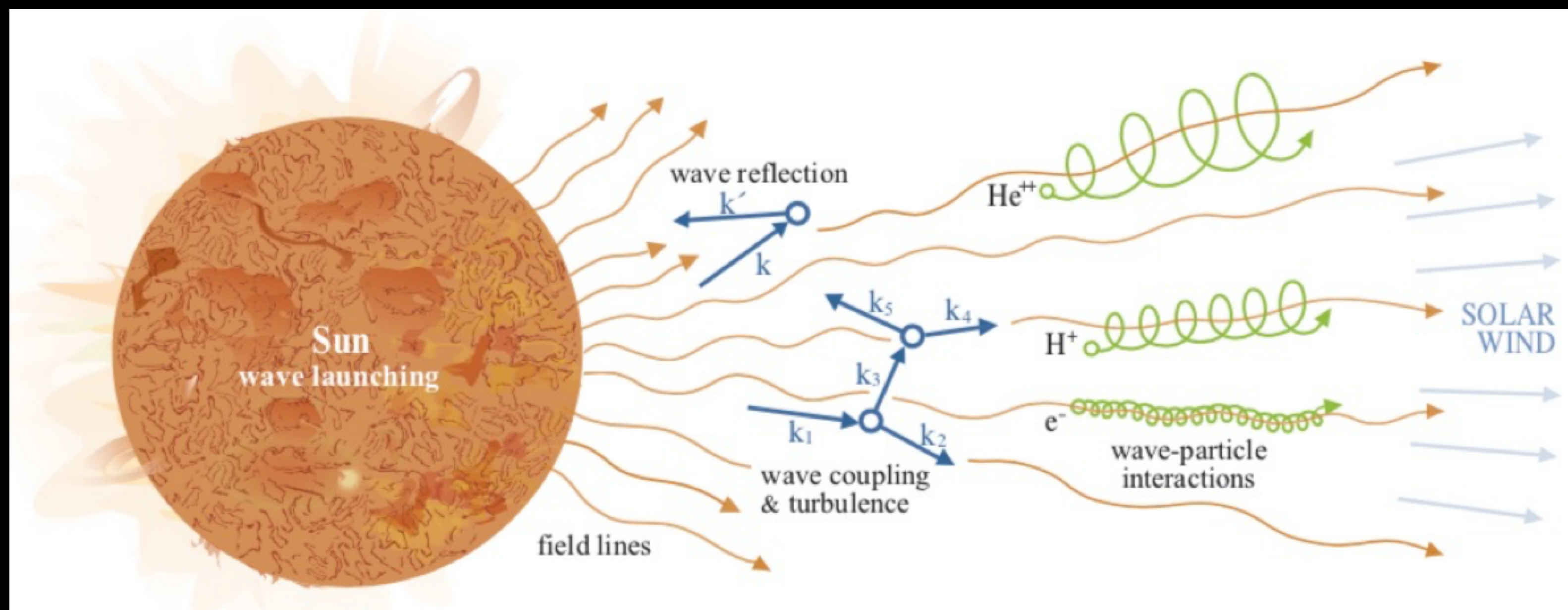






# What we *don't* know

- How is energy transferred to, and dissipated in the solar corona and beyond ?



Cranmer [2019]

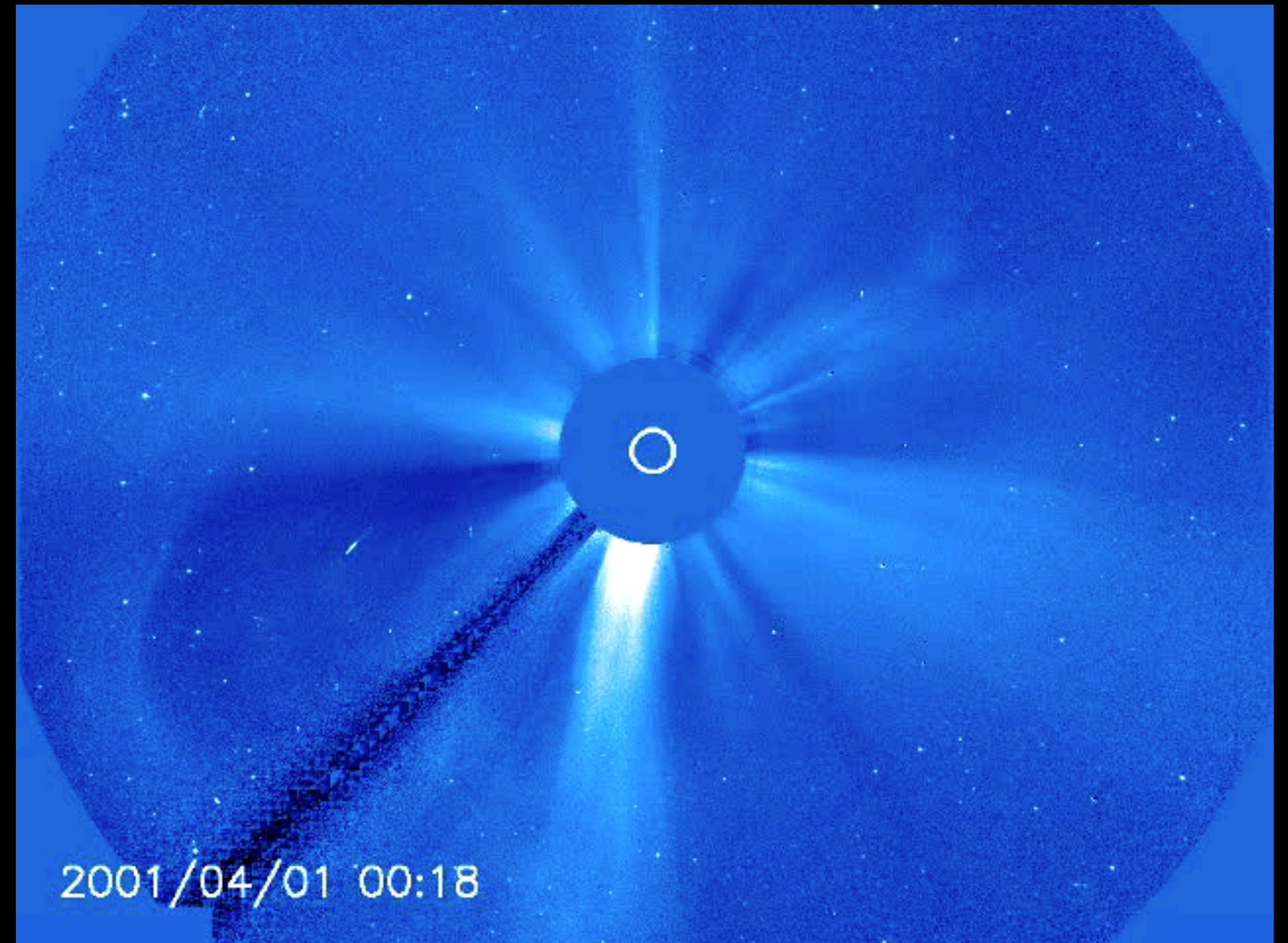
## Plausible candidates:

- Heating by magnetic reconnection
- Low frequency Alfvén waves propagating upwards in open flux tubes, producing ion-cyclotron waves that heat minor ions
- Stochastic heating driven by turbulent fluctuations
- Heating by transients (shocks)
- etc.



# The solar wind ?

- The Sun loses  $\sim 2 \times 10^9$  kg of matter per second  $\rightarrow$  the solar wind
- This highly variable wind affects our terrestrial environment (space weather)

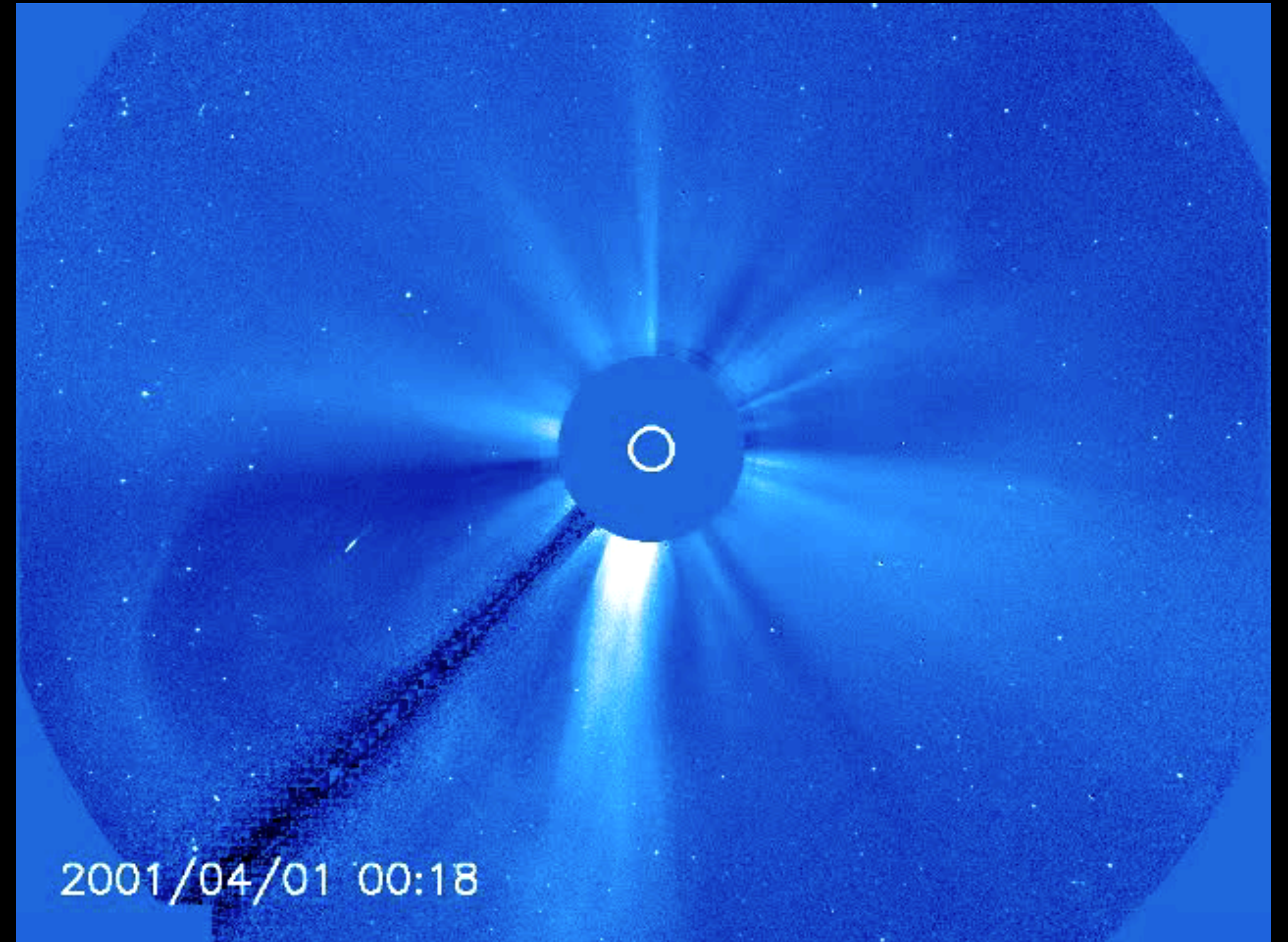


solar corona in white light, seen by a coronagraph [SoHO]



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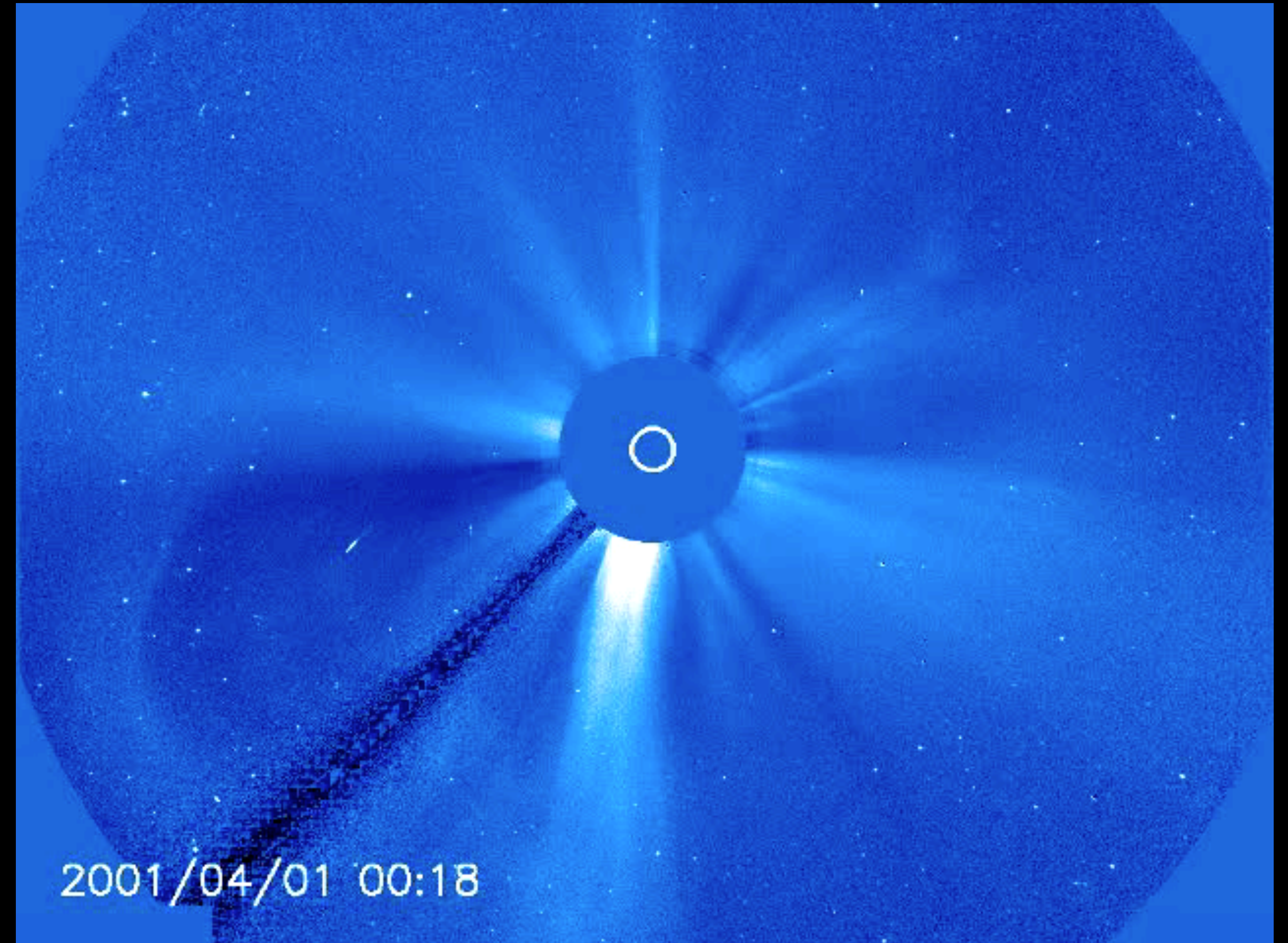


solar corona in white light, seen by a coronagraph [SoHO]



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solar corona in white light, seen by a coronagraph [SoHO]



# What we *don't* know

- How does the magnetic field in the solar wind source regions connect to the heliosphere?

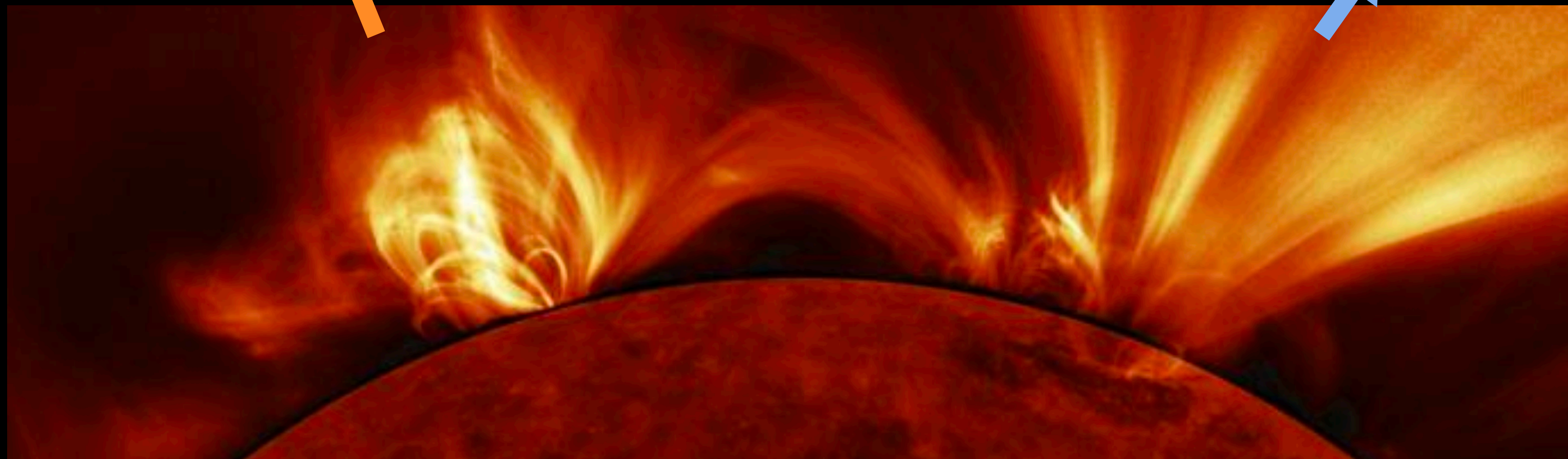
closed magnetic field lines

→ slow wind

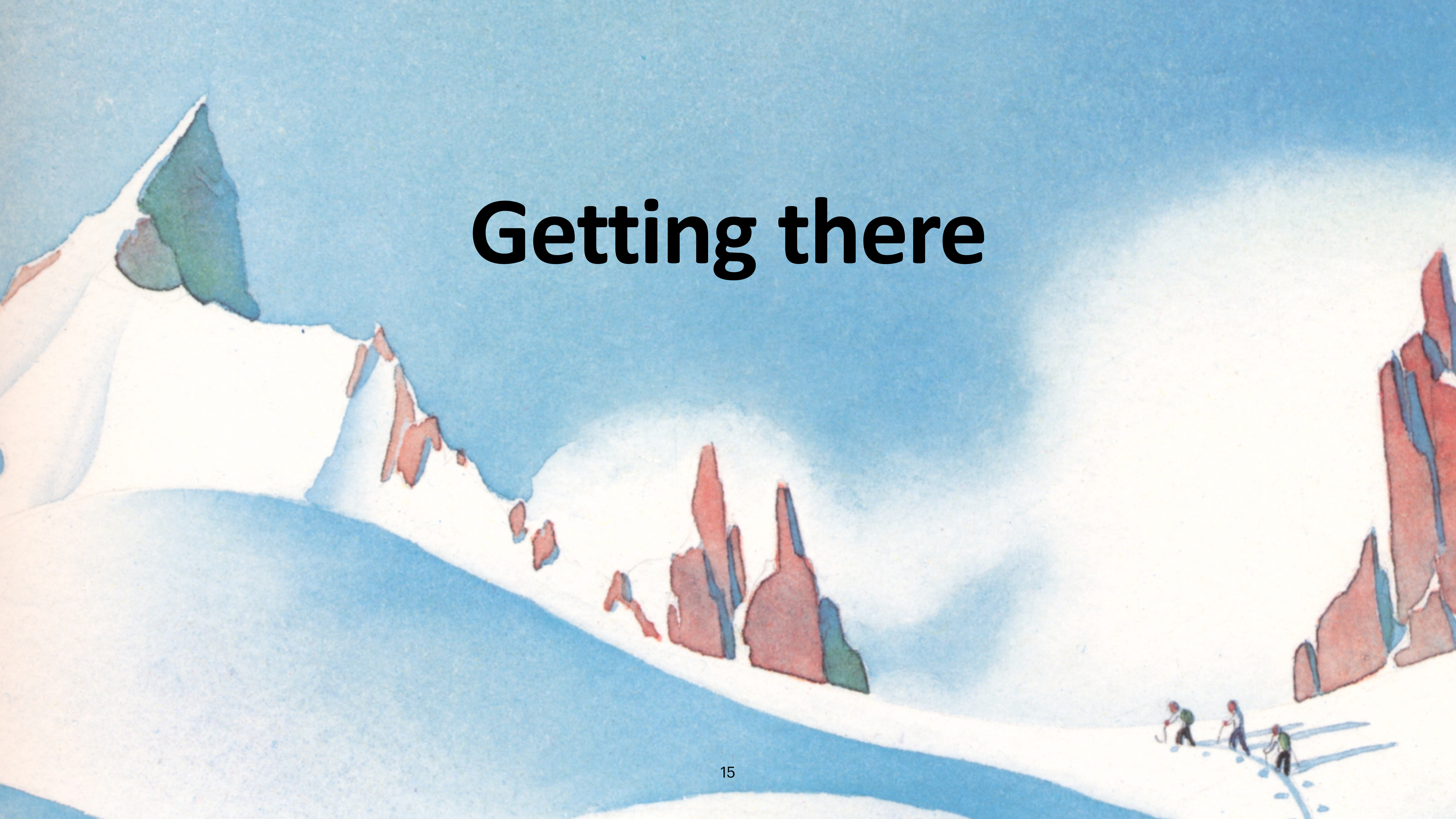


open magnetic field lines

→ fast wind



# Getting there

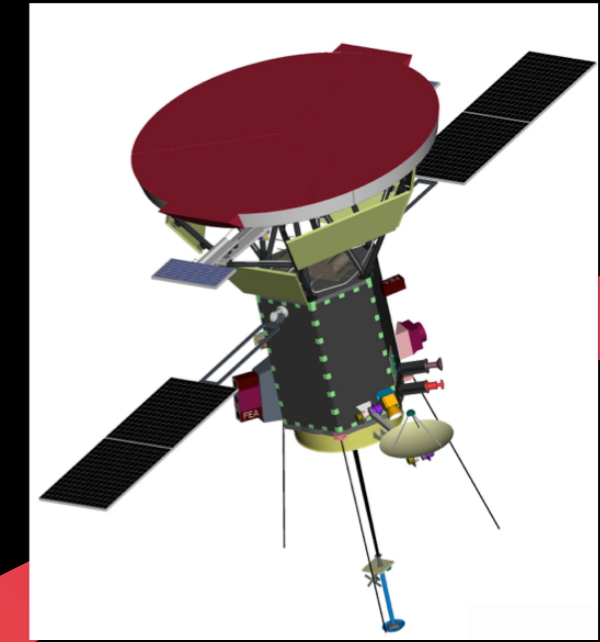




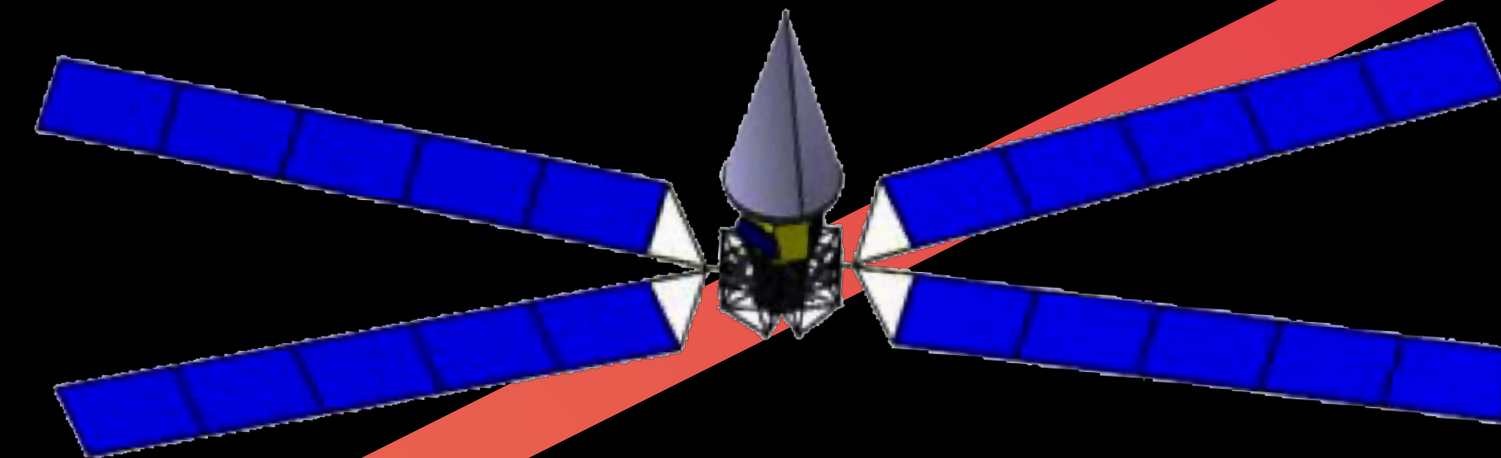
# A long history of mission concepts

Major bottlenecks are

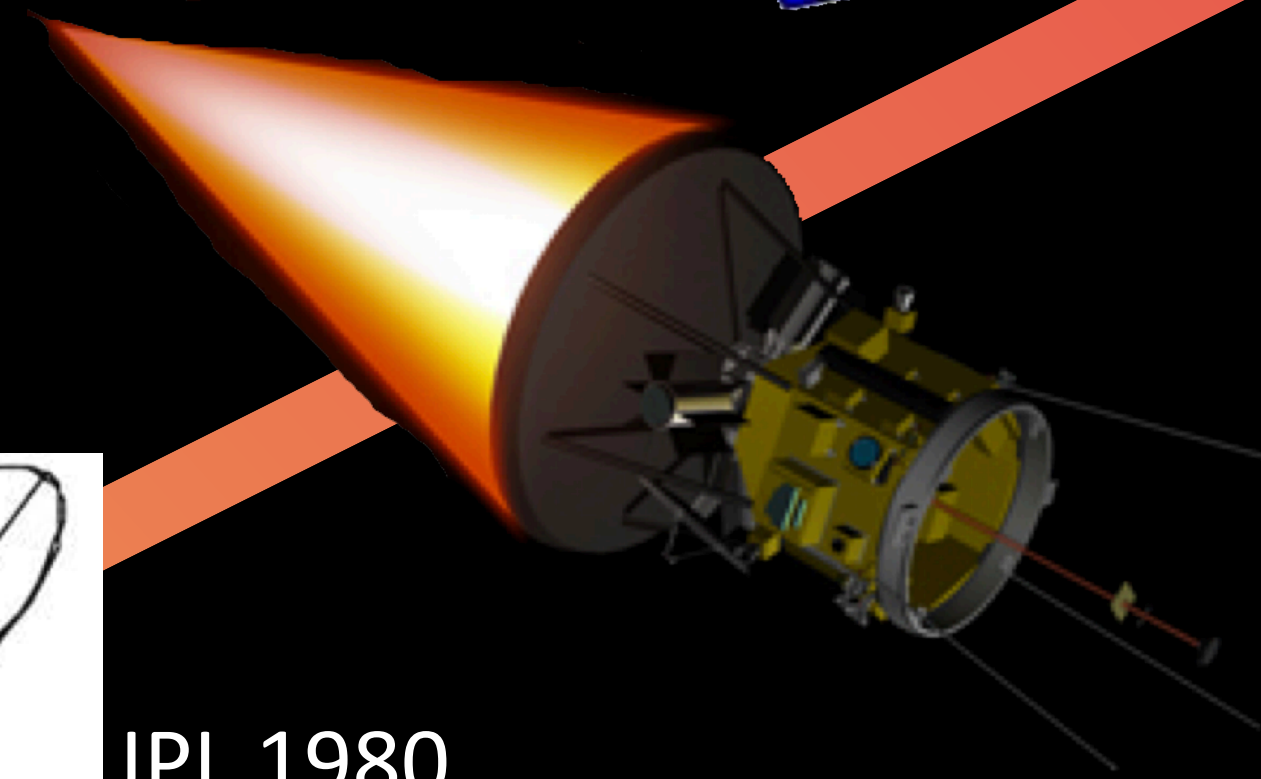
- thermal design
- powerful launcher to rapidly get to the Sun



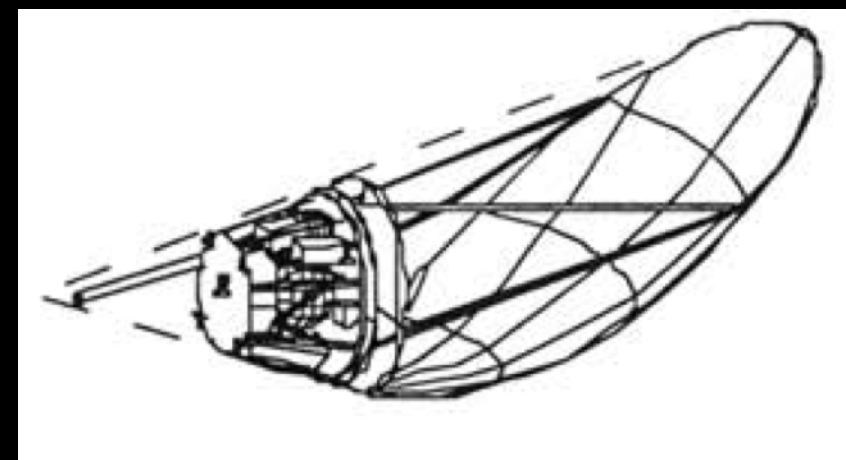
Solar Probe Plus 2010



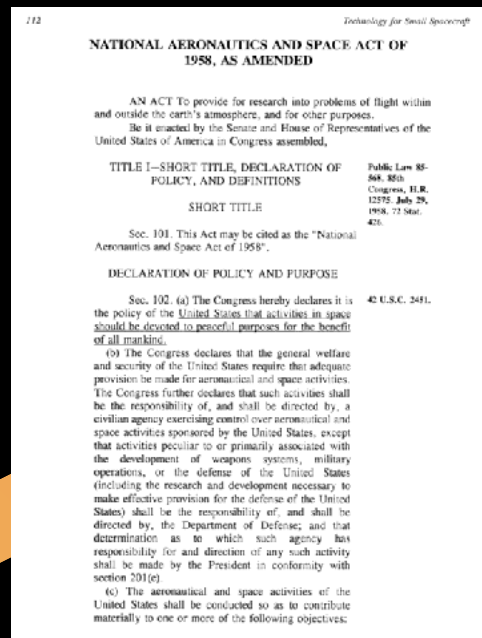
PHOIBOS 2008



Solar Probe 2005



JPL 1980



National Research Council 1958



# The instruments

- 4 Instrument suites:
- 3 for in-situ observations of waves and particles,
- 1 imager for visible light

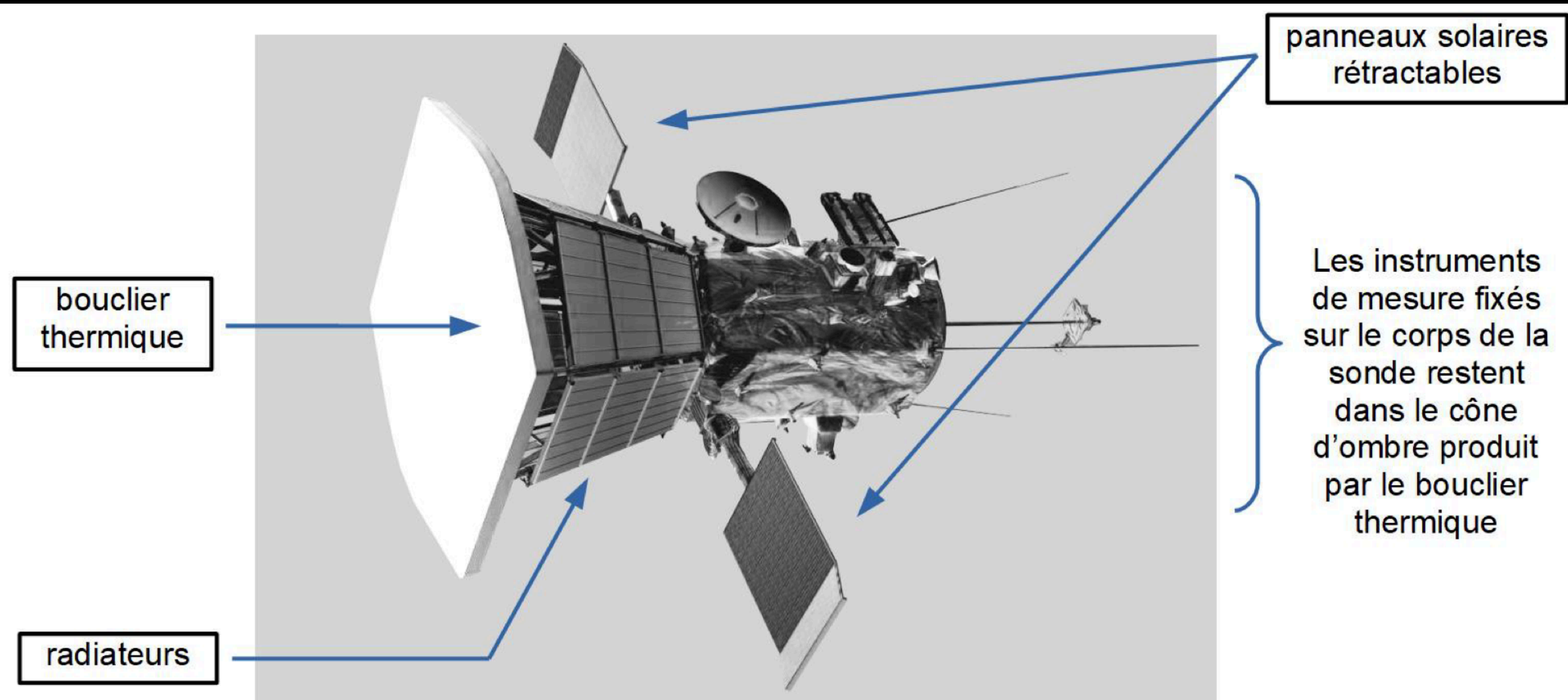


figure 1 - Sonde PSP (Parker Solar Probe) Source : [blogs.nasa.gov](https://blogs.nasa.gov)

Sujet du Bac (2021)





# The instruments

- 4 Instrument suites:
- 3 for in-situ observations of waves and particles,
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Magnetic sensor from LPC2E



Les instruments de mesure fixés sur le corps de la sonde restent dans le cône d'ombre produit par le bouclier thermique

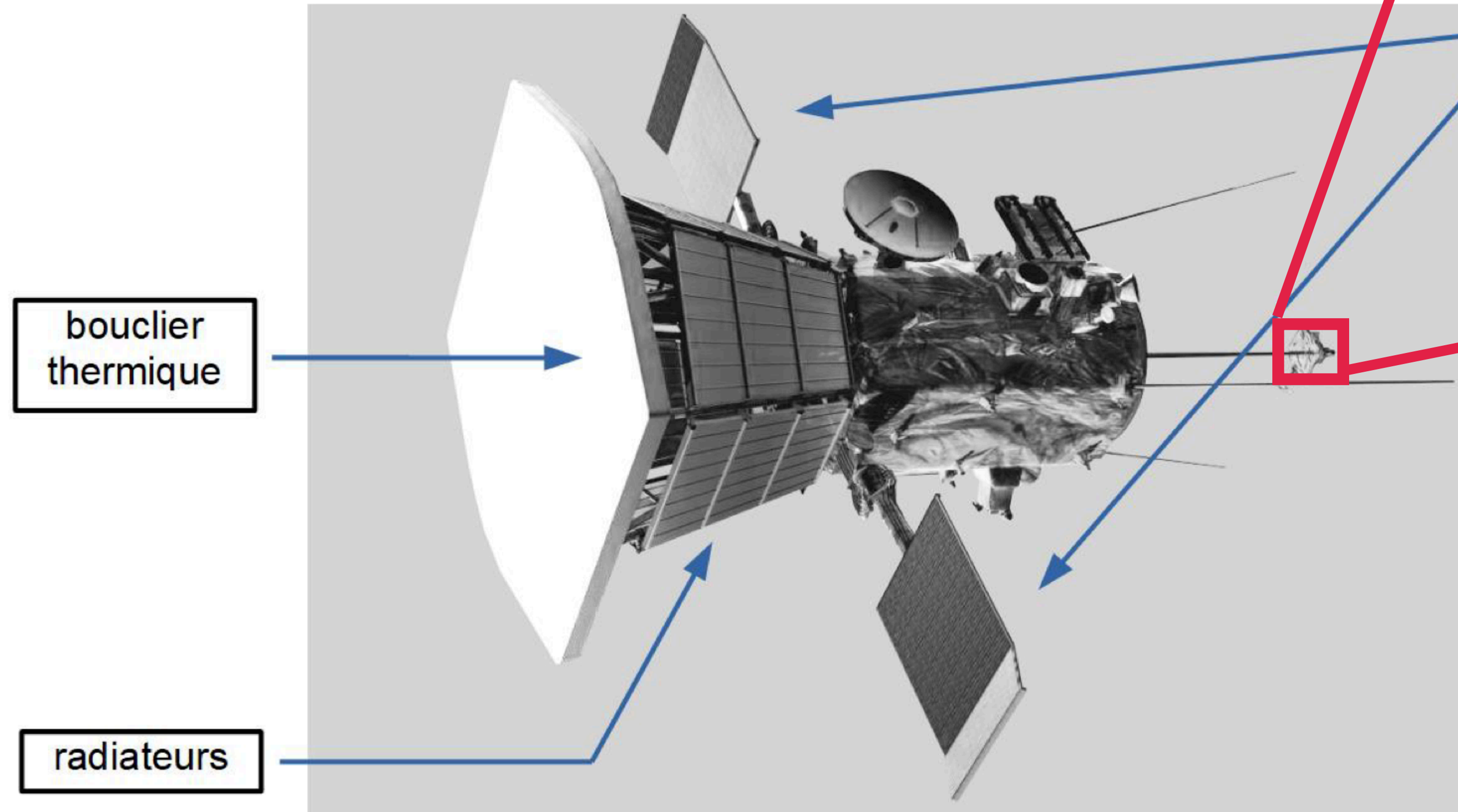


figure 1 - Sonde PSP (Parker Solar Probe)

Source : [blogs.nasa.gov](https://blogs.nasa.gov)

Sujet du Bac (2021)



# Strong French involvement



+



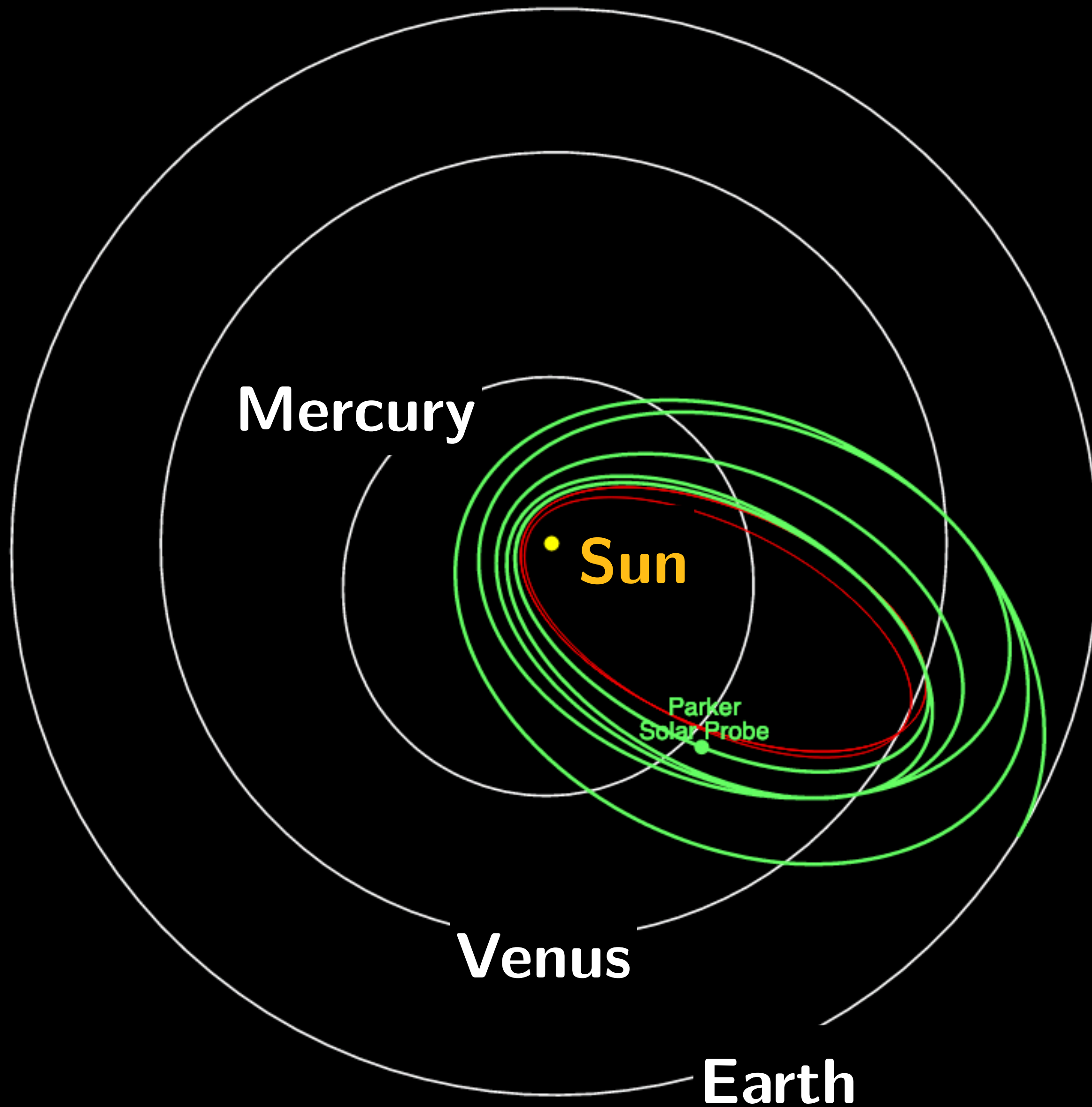


# Launch (August 12, 2018)





# Mission profile



- 25 Solar encounters between 2018 and 2025
- Closest perihelion (in 2025) :  $9.8 R_{\odot} = 0.048 \text{ AU}$
- Max velocity :  $690'000 \text{ km/h} = c/1560$

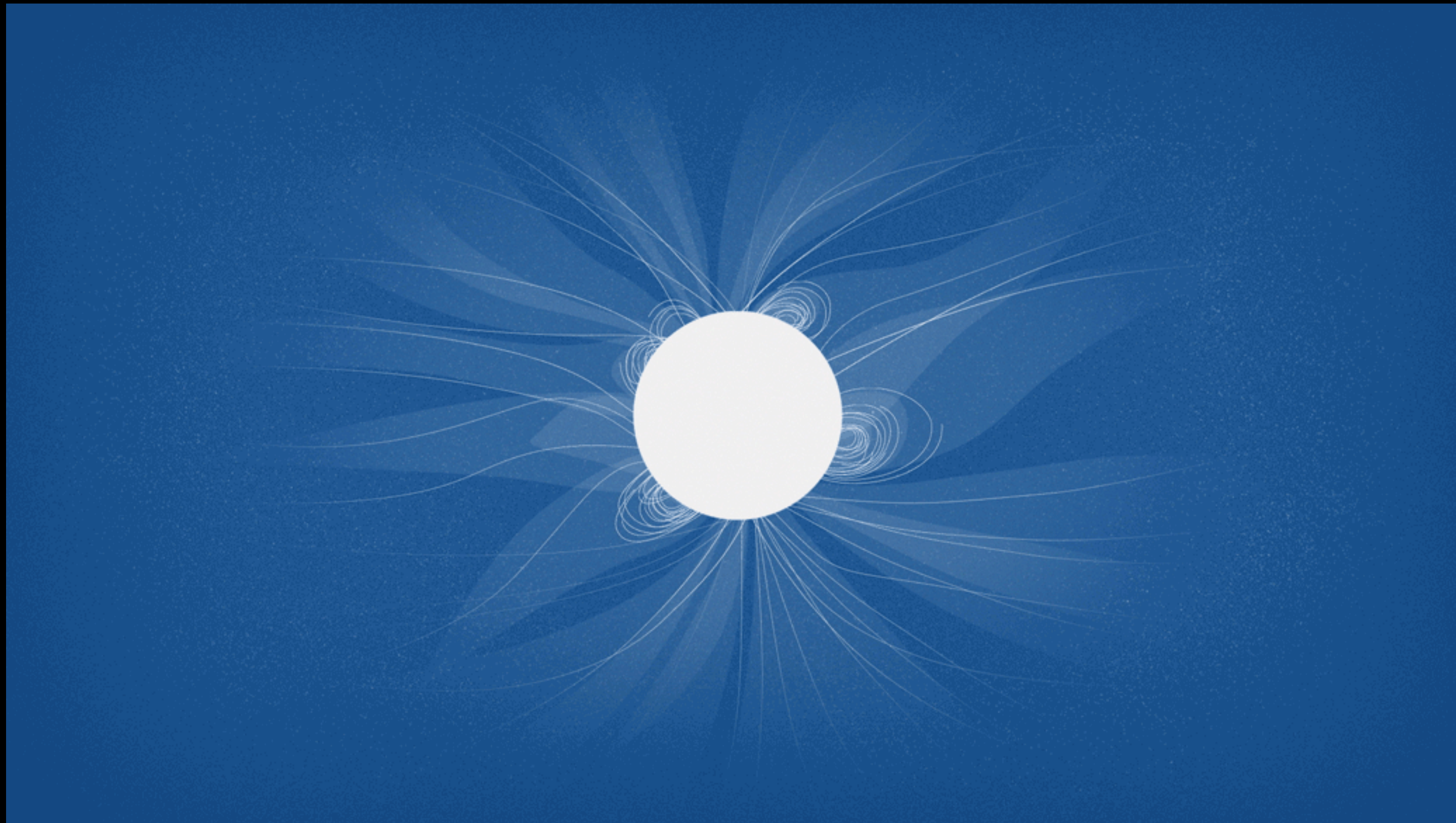


**What we found so far**



# First results

What we were expecting

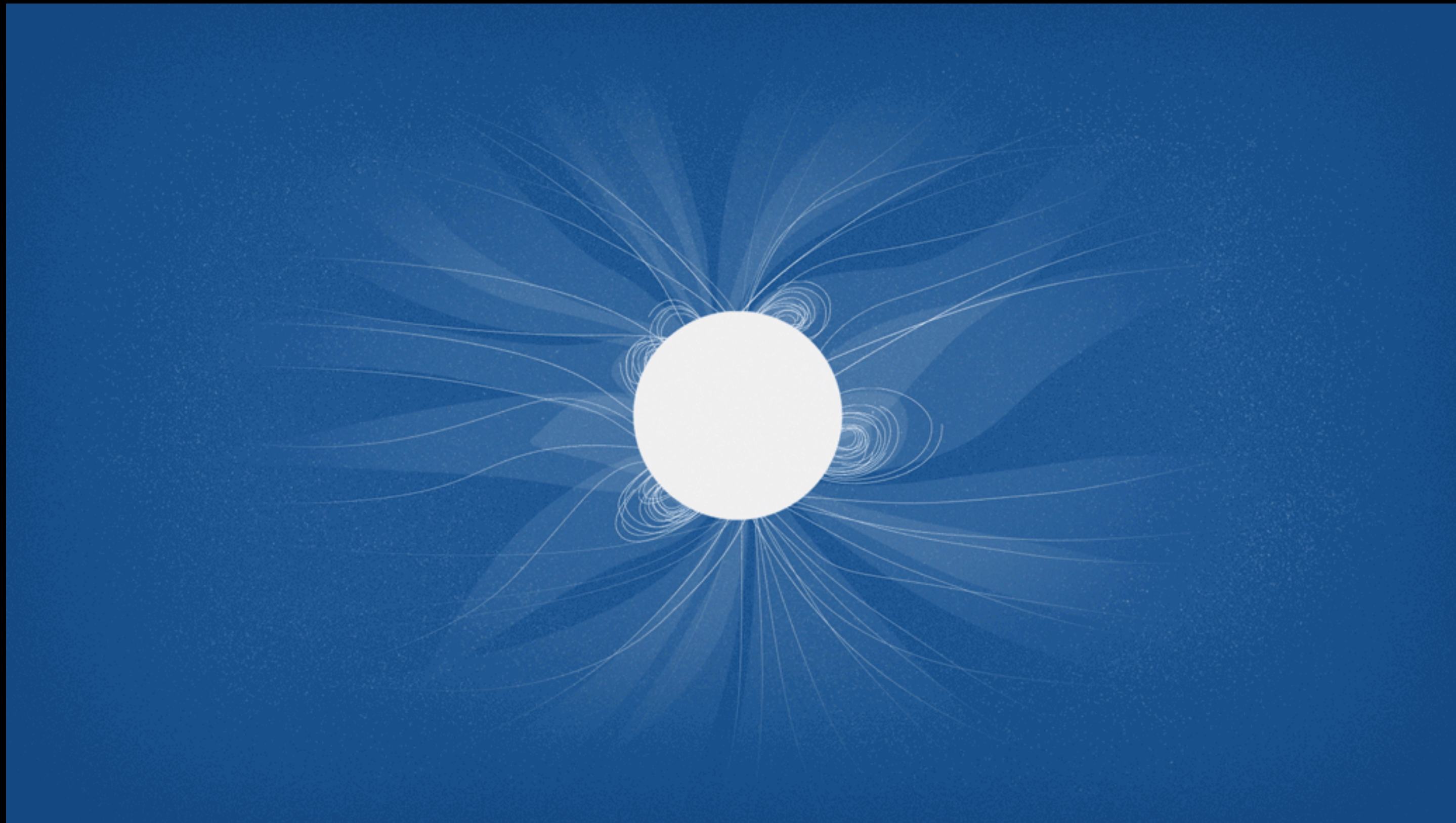


NASA [2023]



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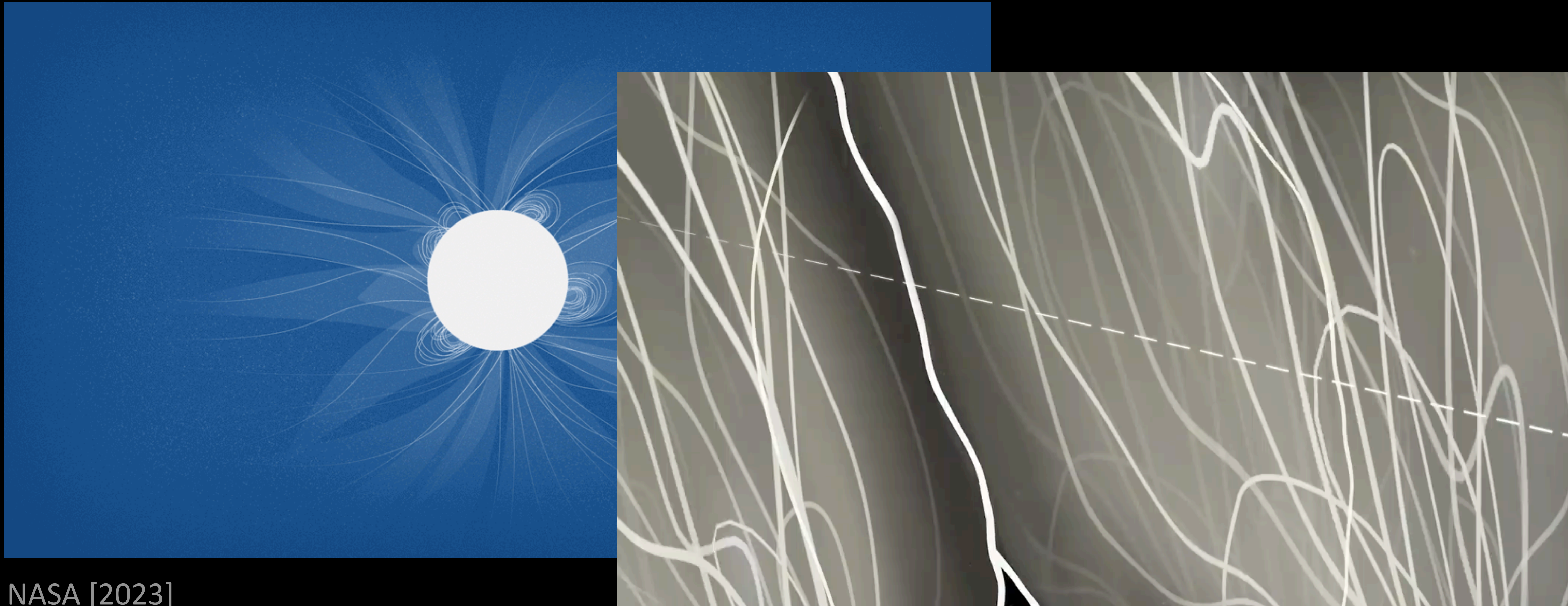


NASA [2023]



# First results

What we found : a pristine solar wind that is much more structured than expected



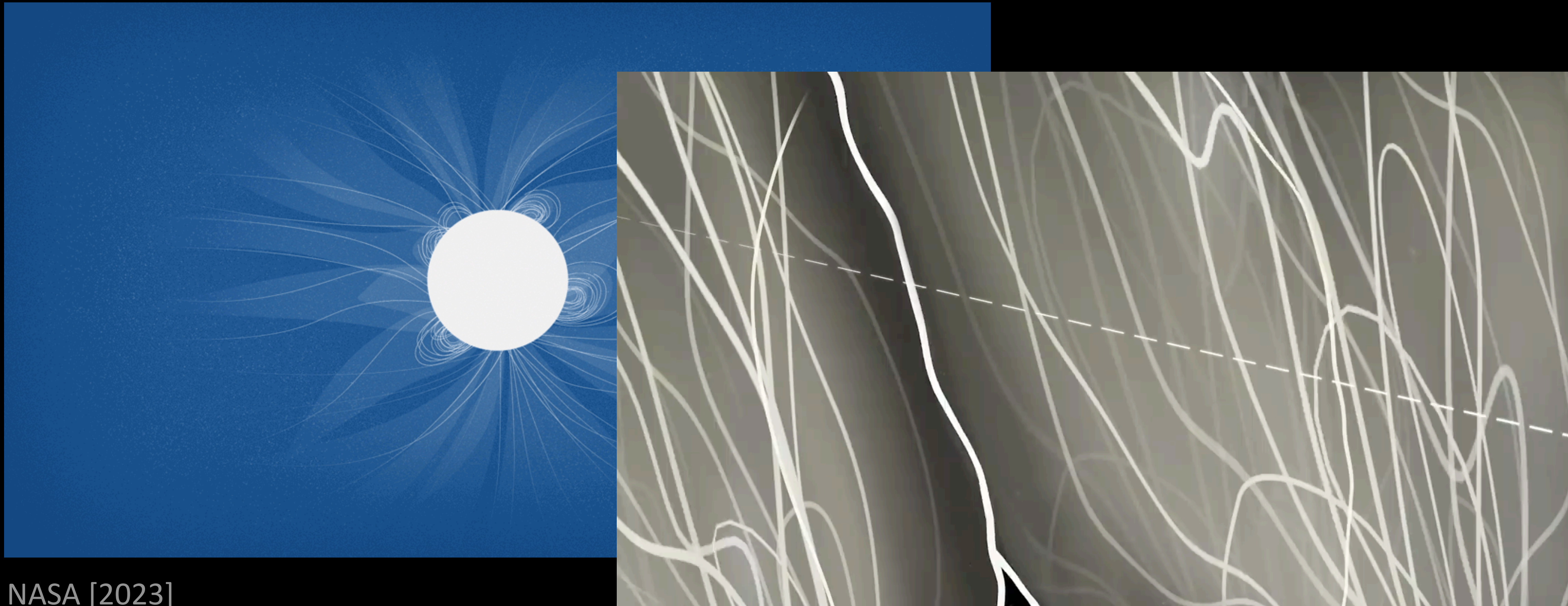
NASA [2023]





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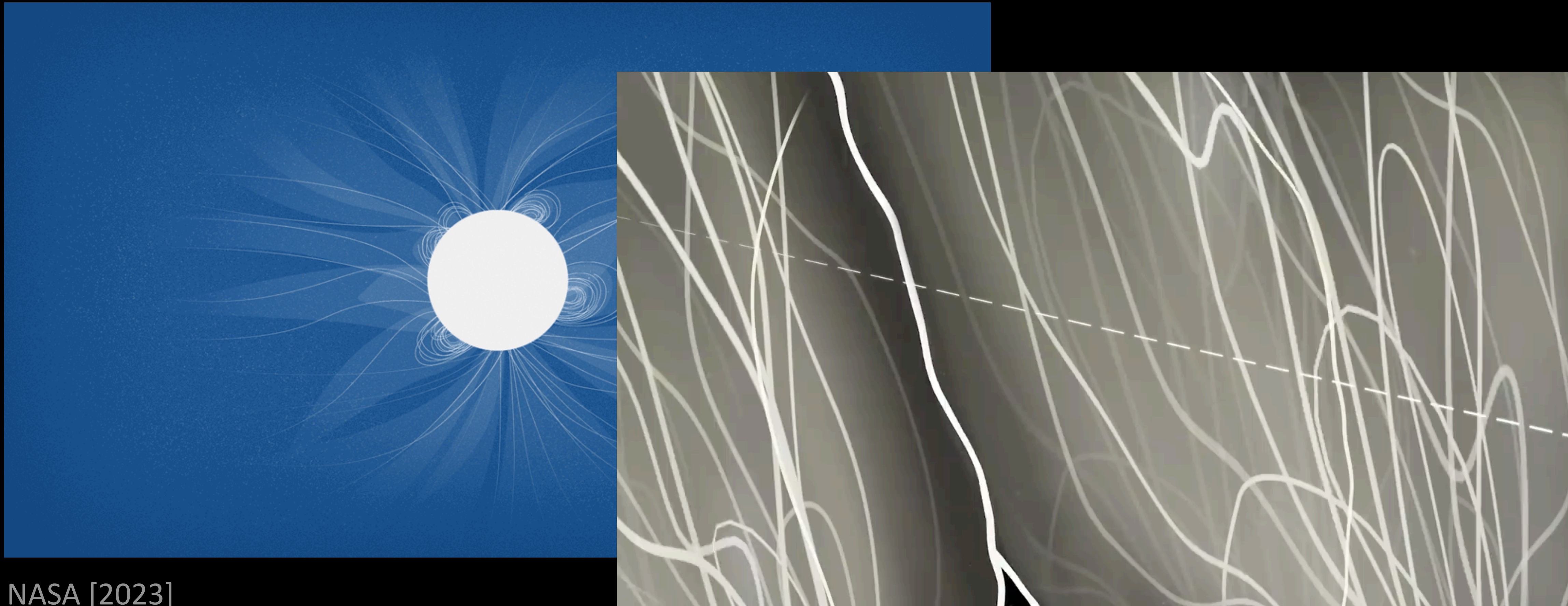


NASA [2023]



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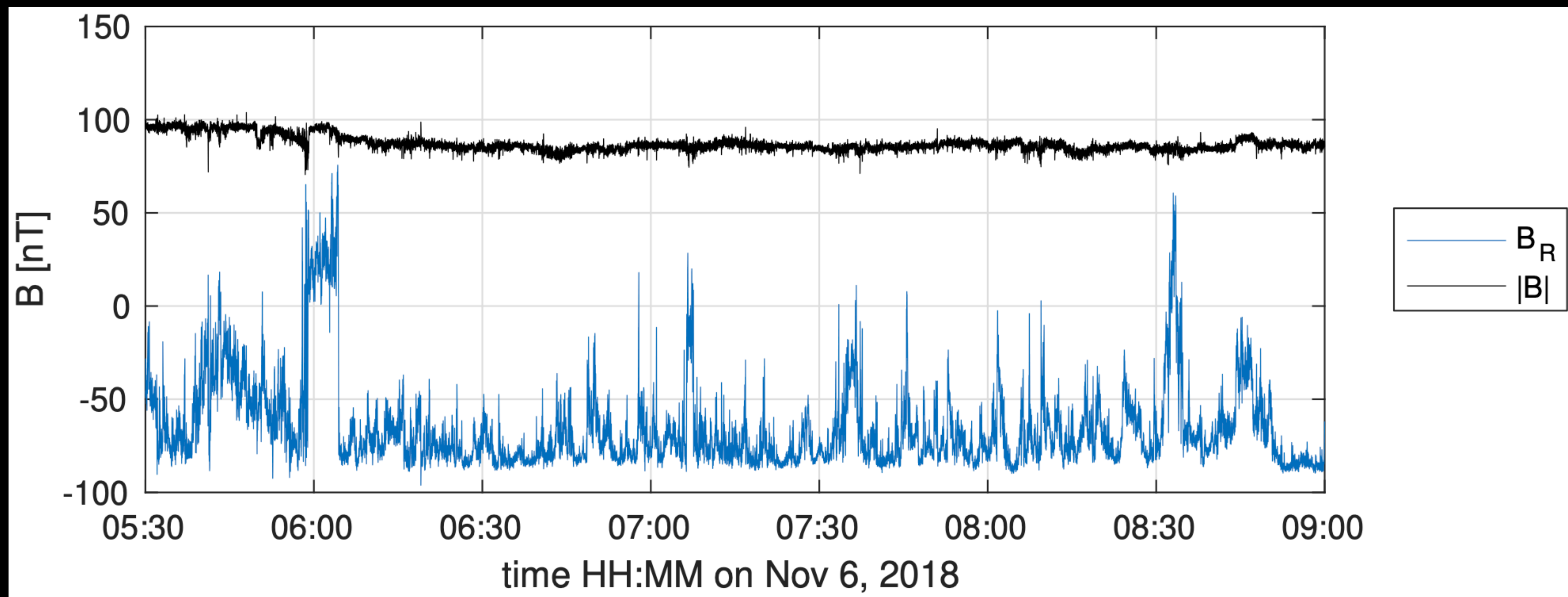


NASA [2023]



# Switchbacks

- Obiquitous deflections of the radial magnetic field, called “switchbacks”



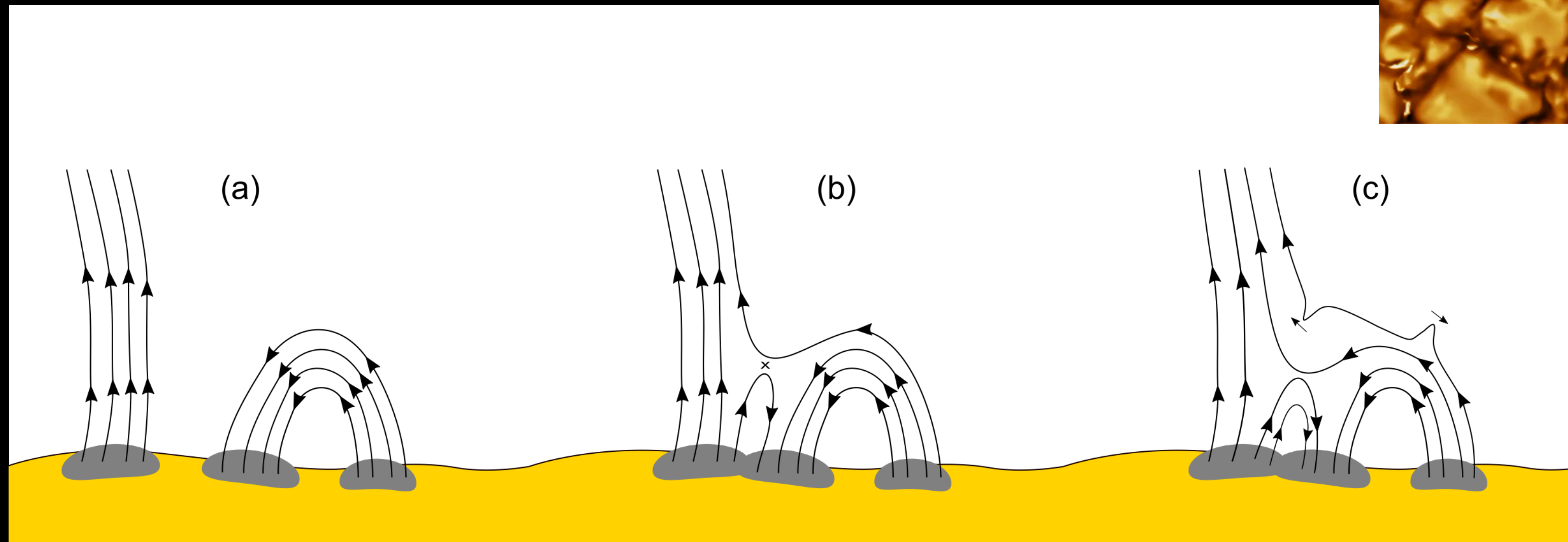
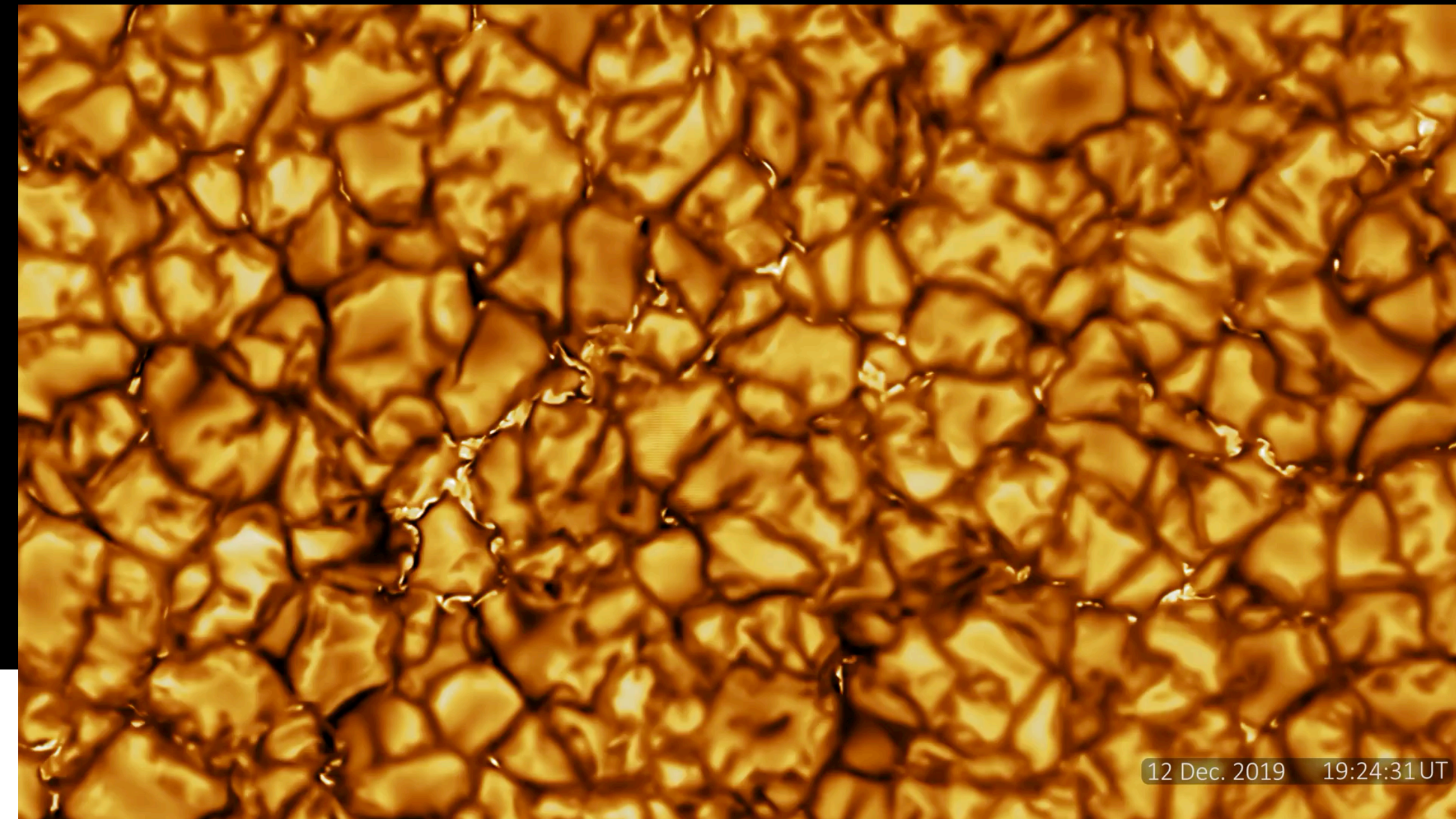
Radial component of the magnetic field [nT]



# What is the origin of switchbacks ?

Bénard cells at the solar photosphere

- Are switchbacks generated deep in the corona or locally ?
- How much do they contribute to the energetics of the solar wind ?

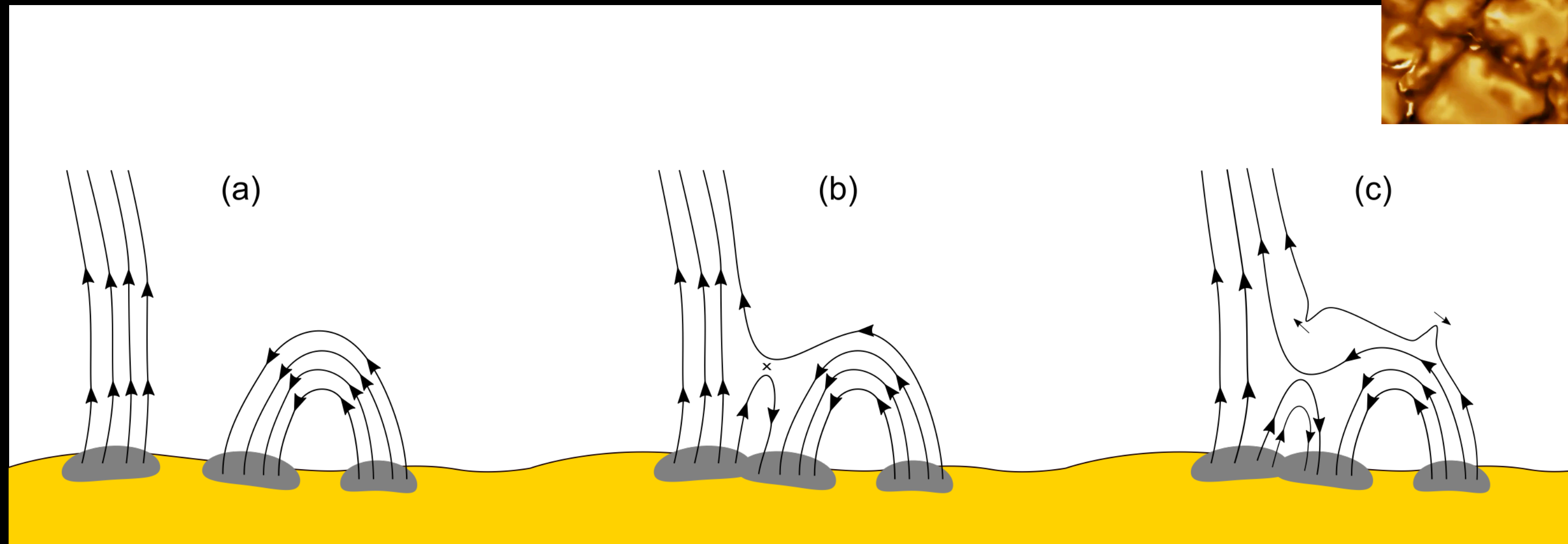
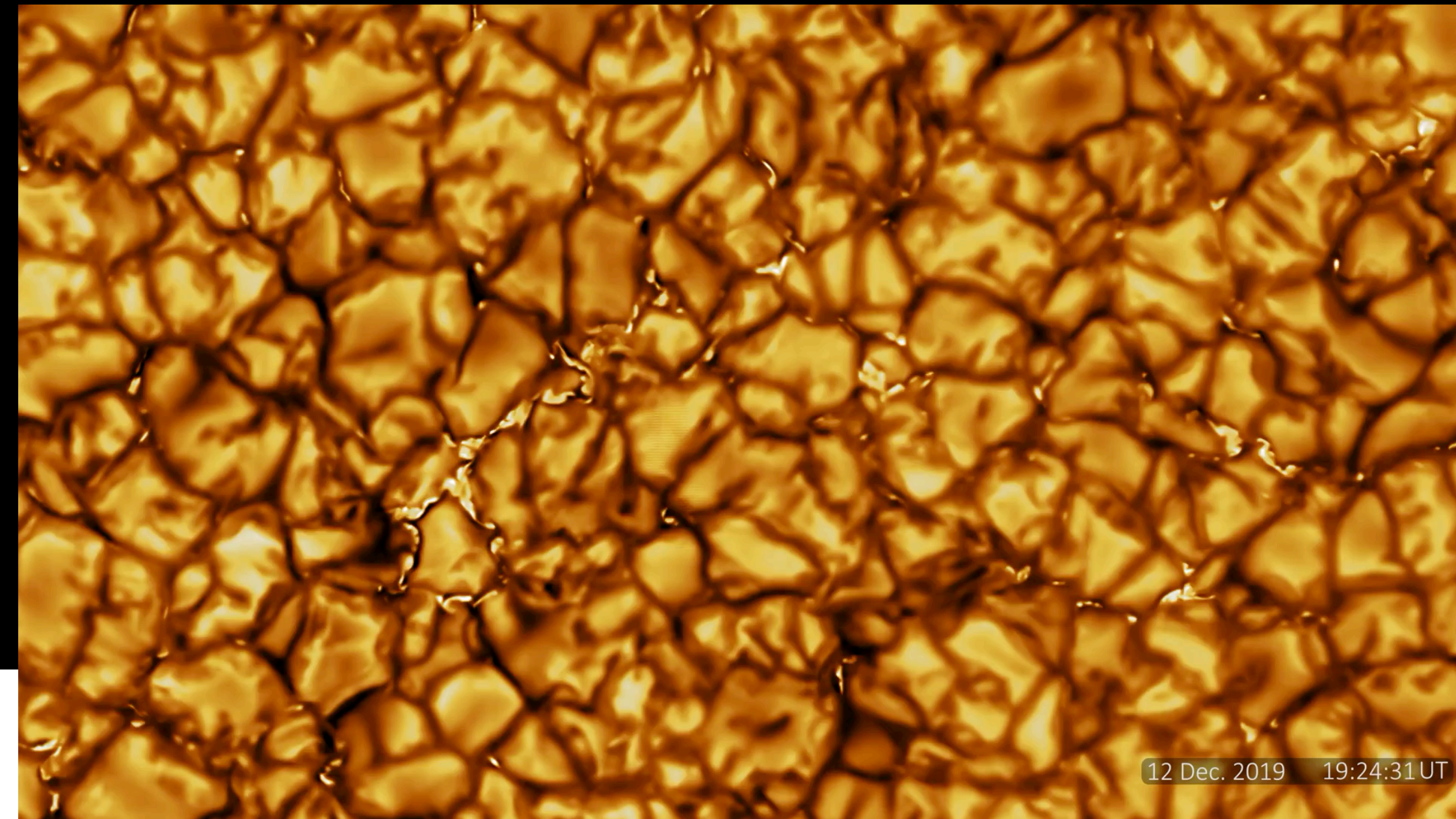




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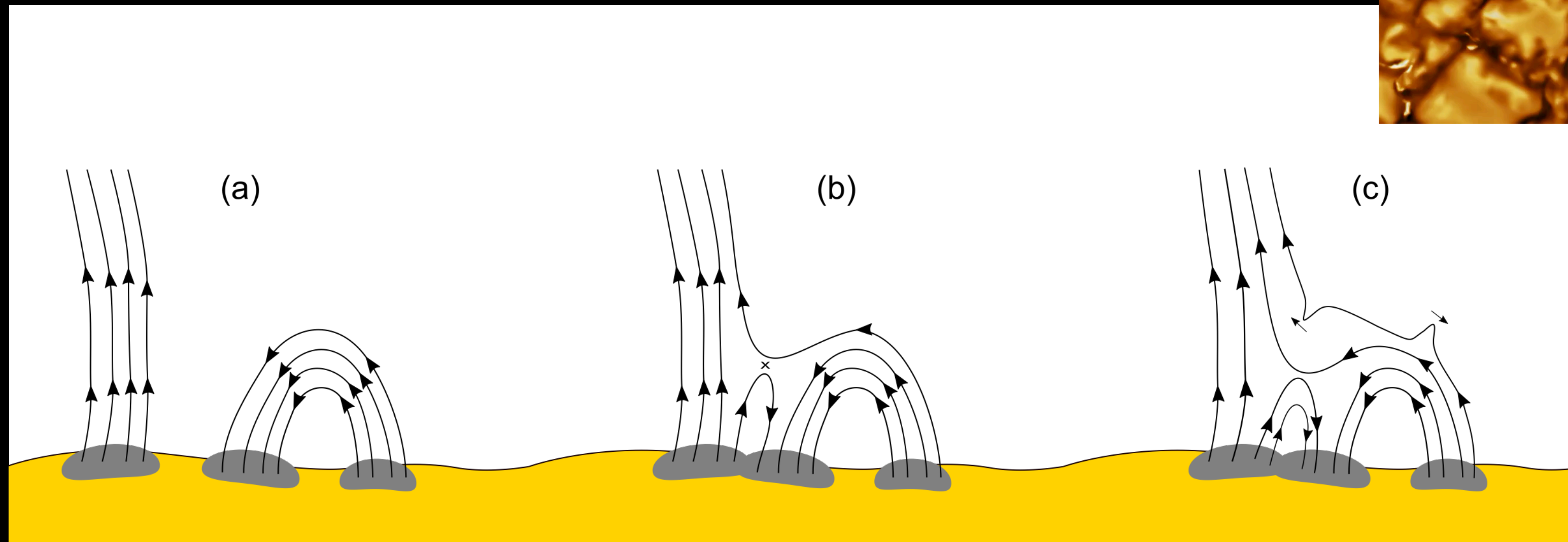
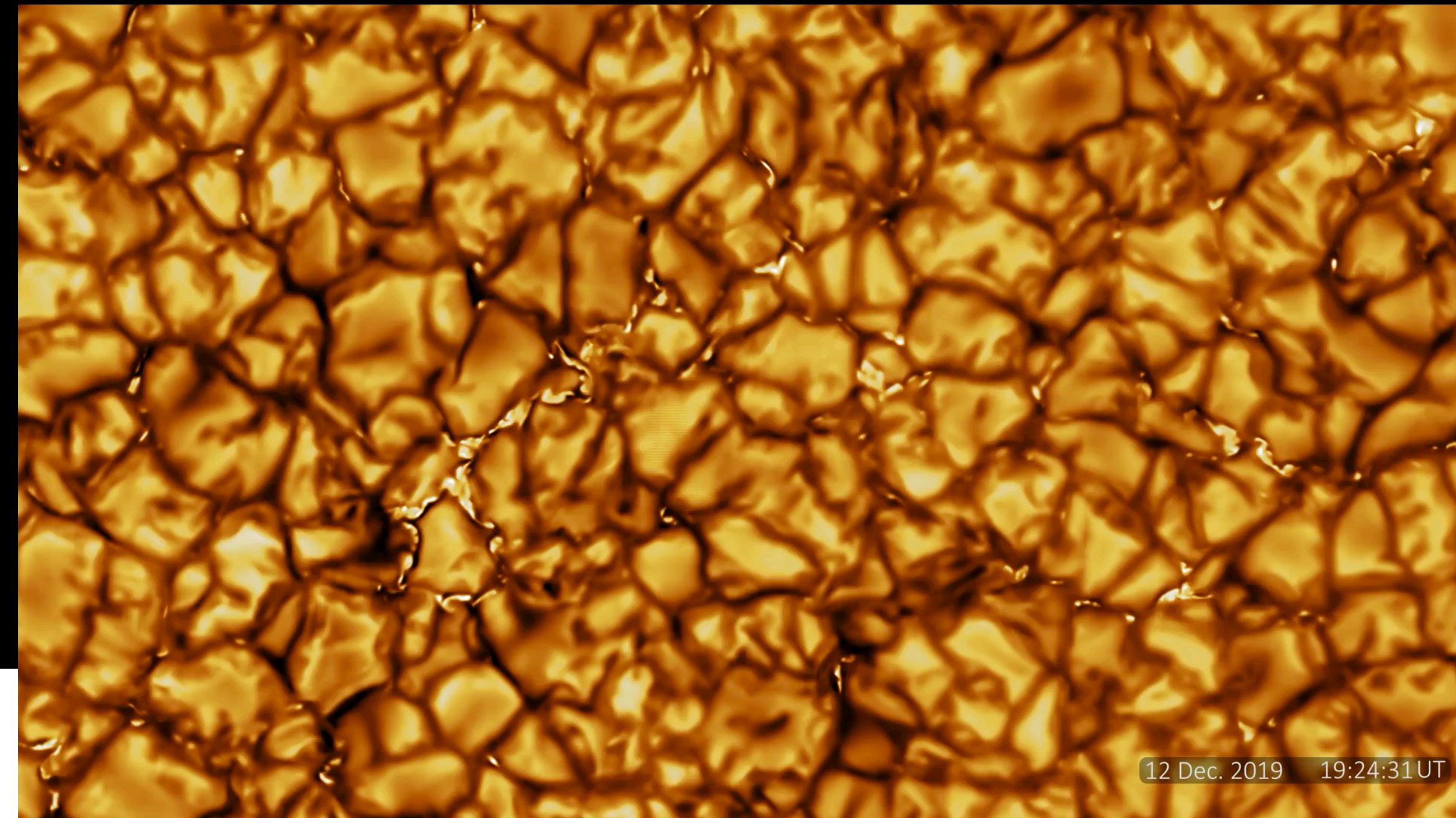




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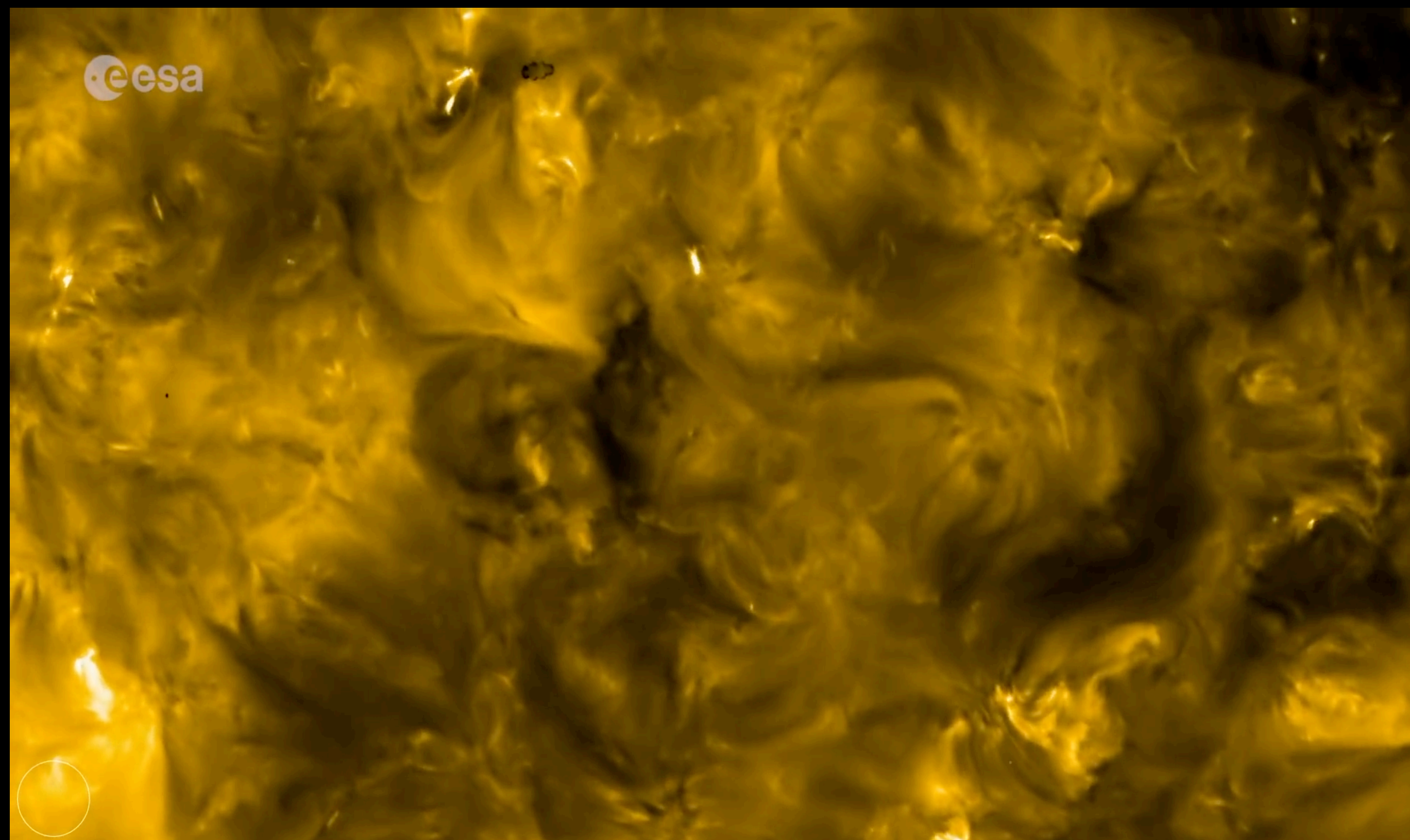
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# Small-scale features play a dominant role

- EUV images from ESA's Solar Orbiter mission reveal omnipresent brightenings
- These should bring a major contribution to coronal heating

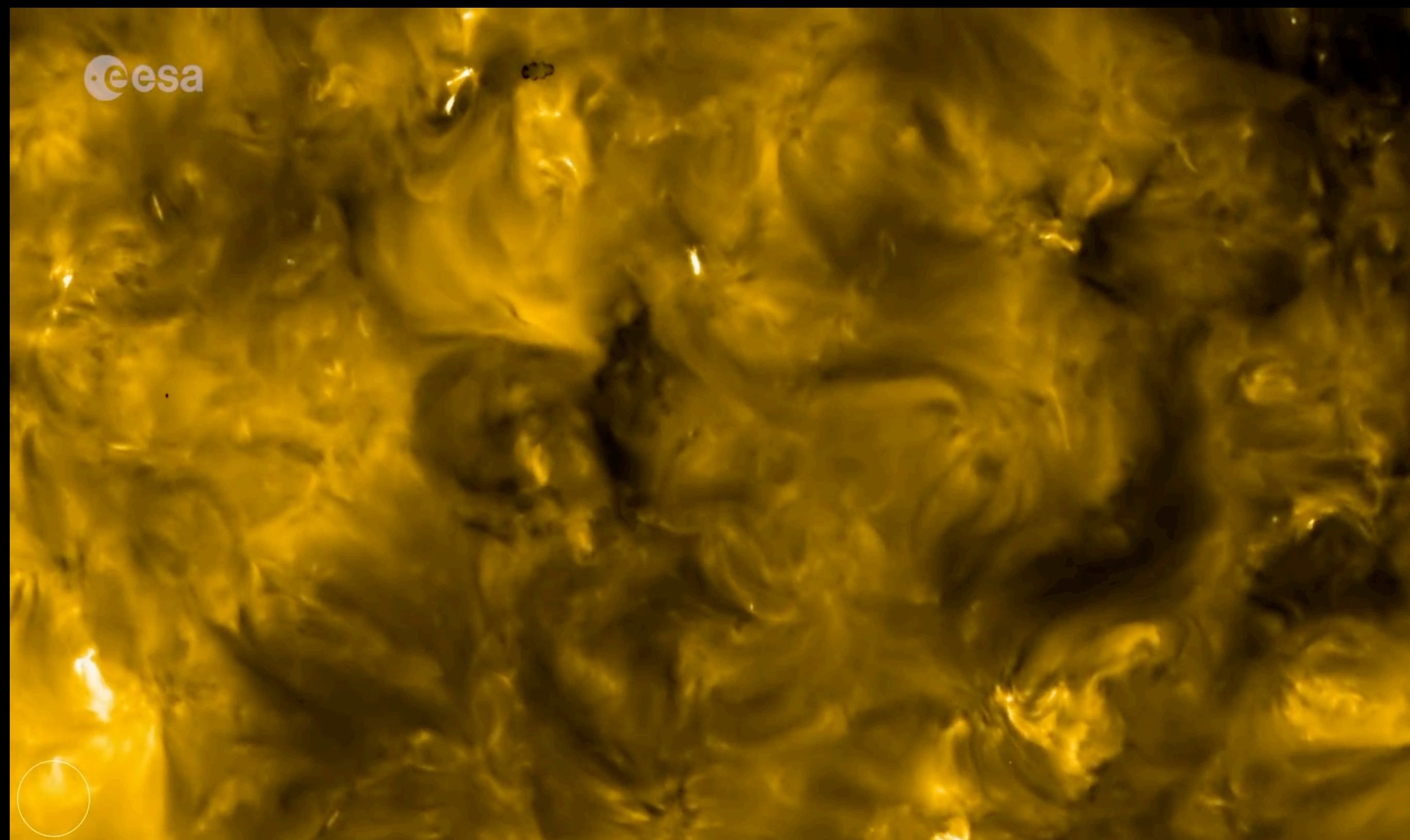


SoLO/EUI wavelength 17.1 nm



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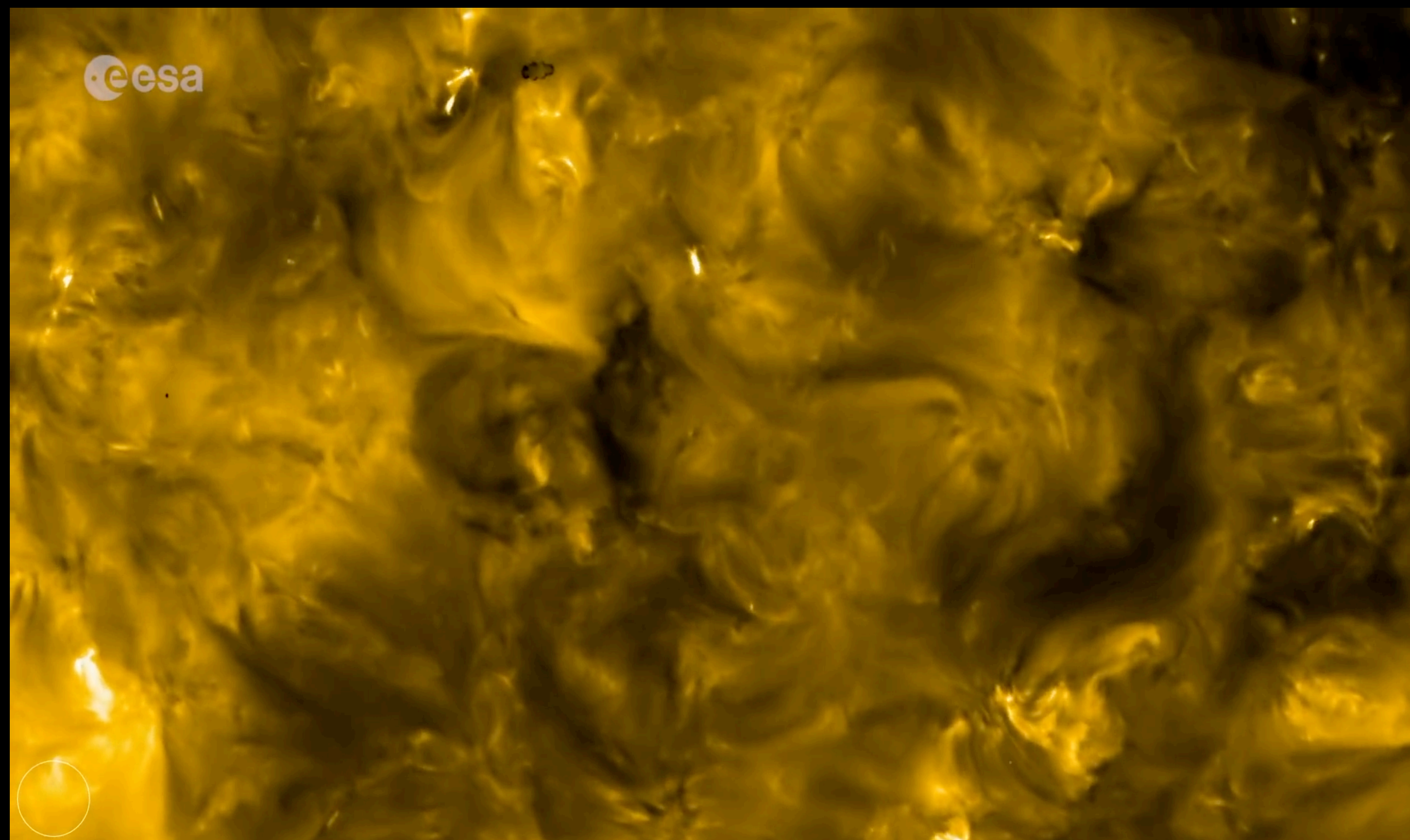
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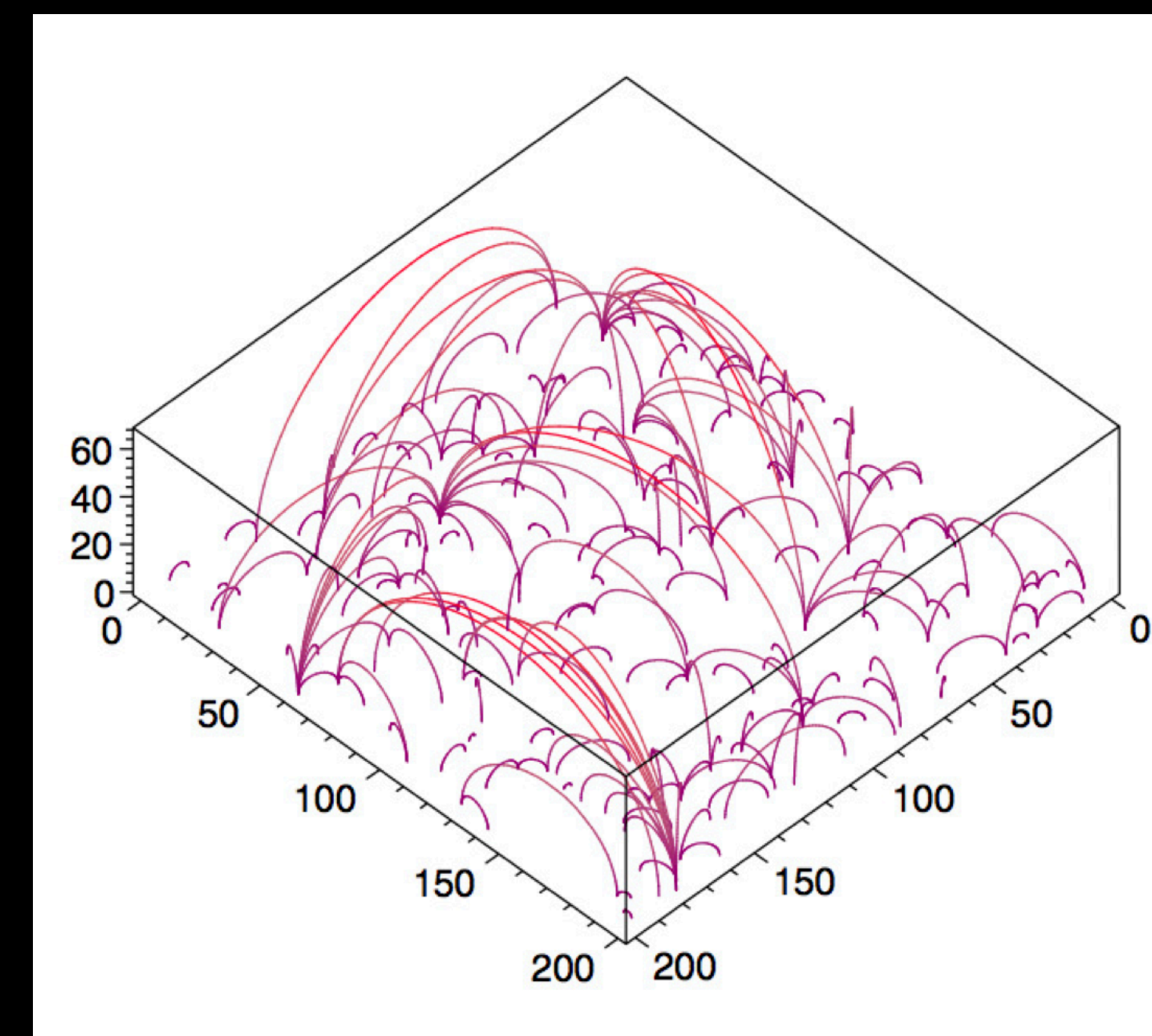


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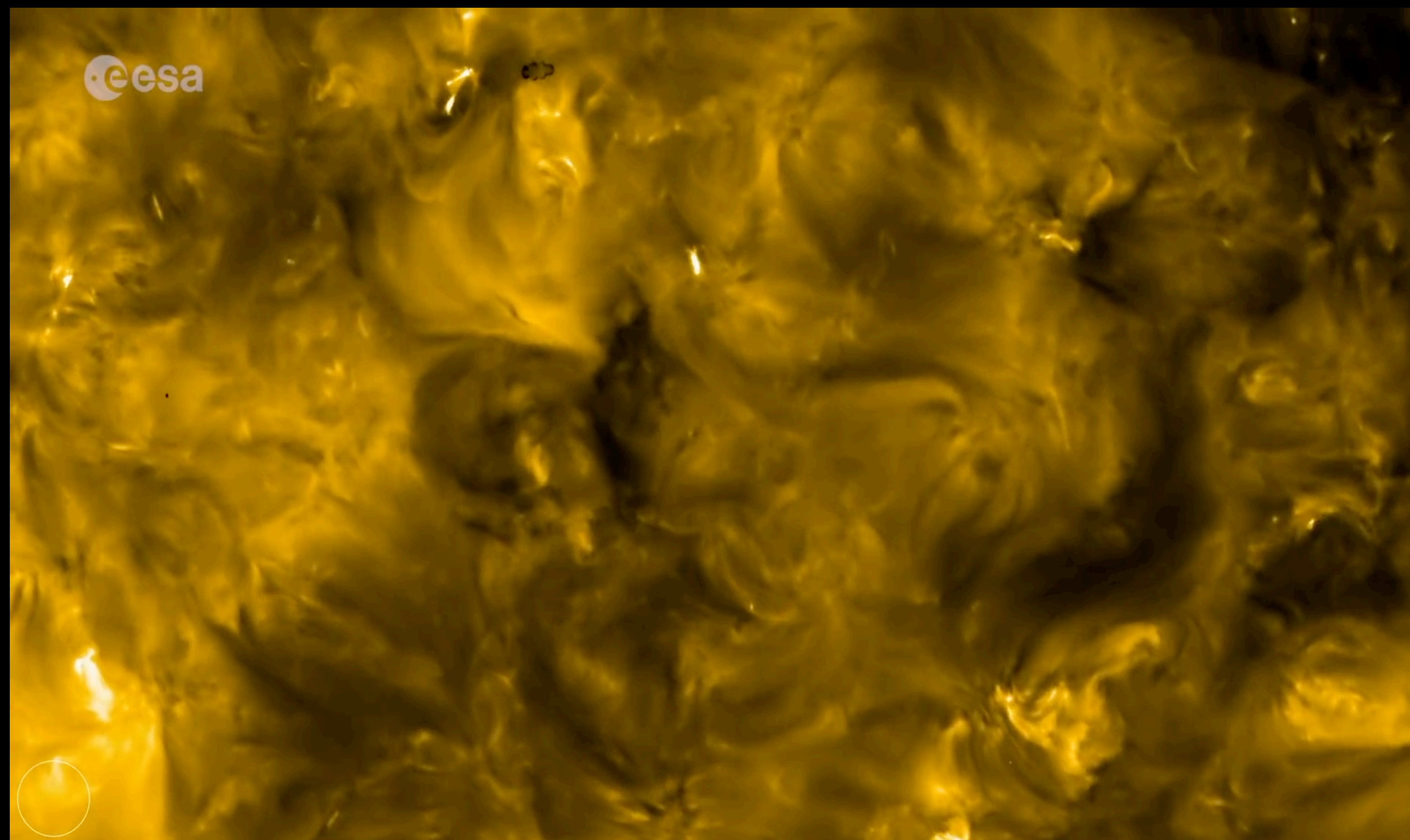


Hughes [2003]

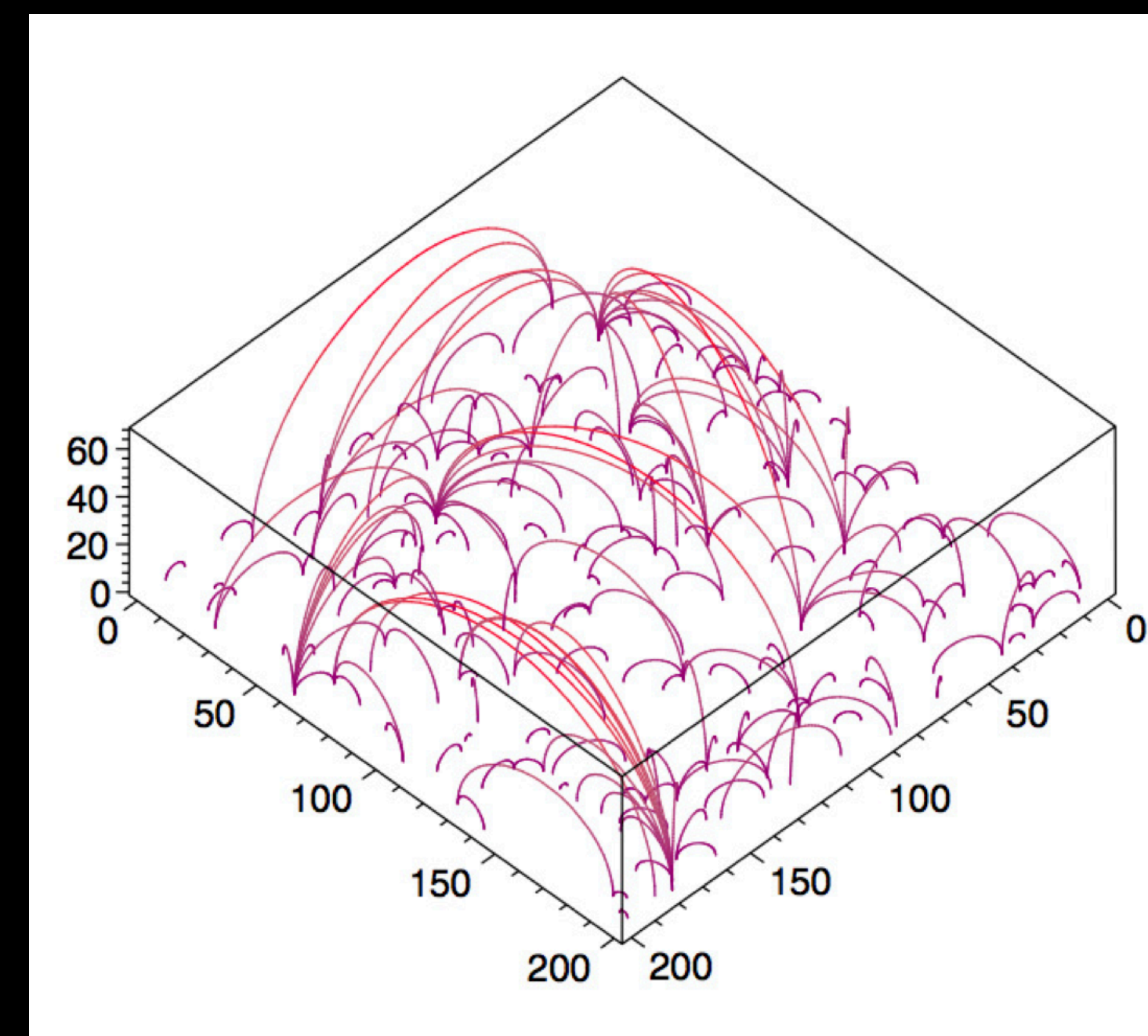


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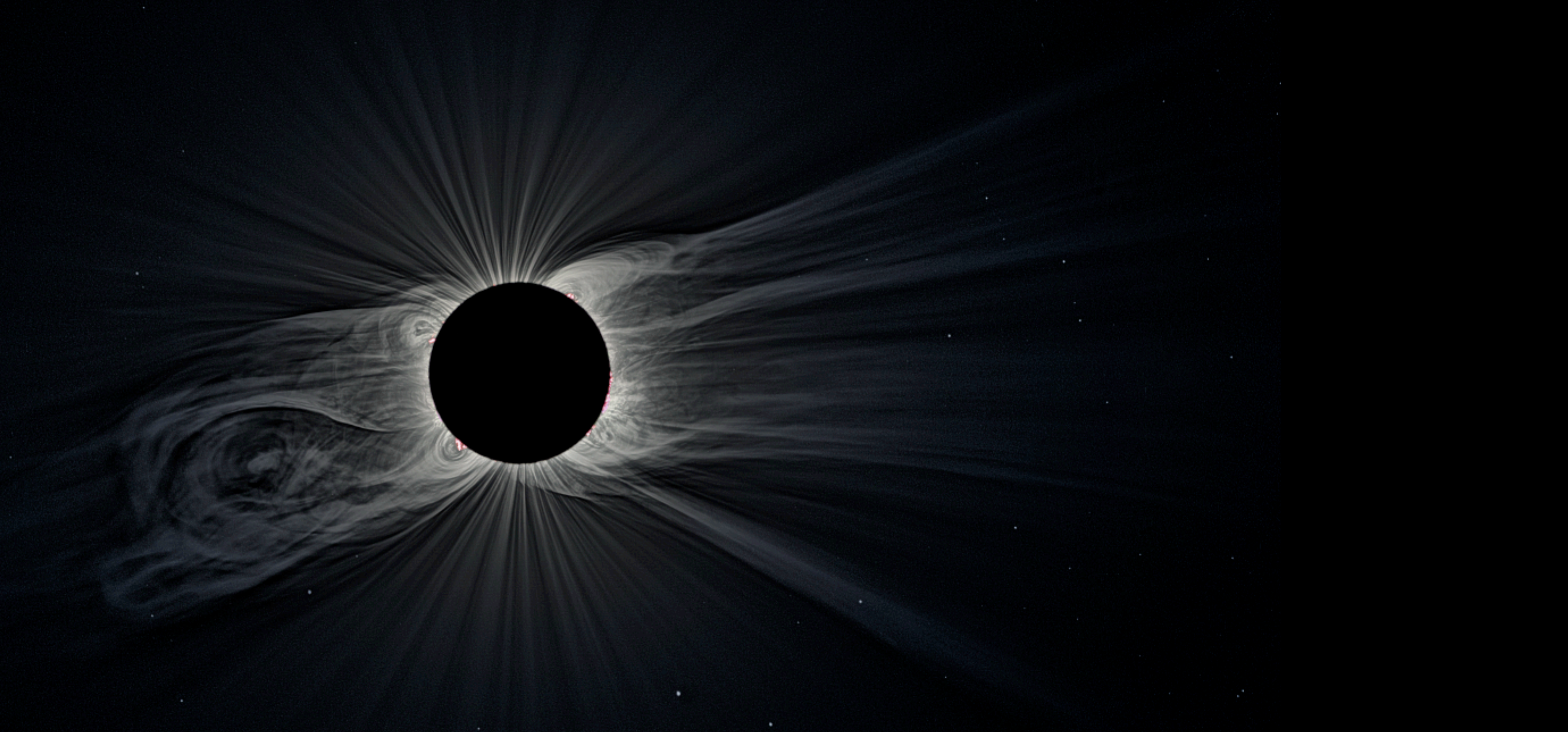


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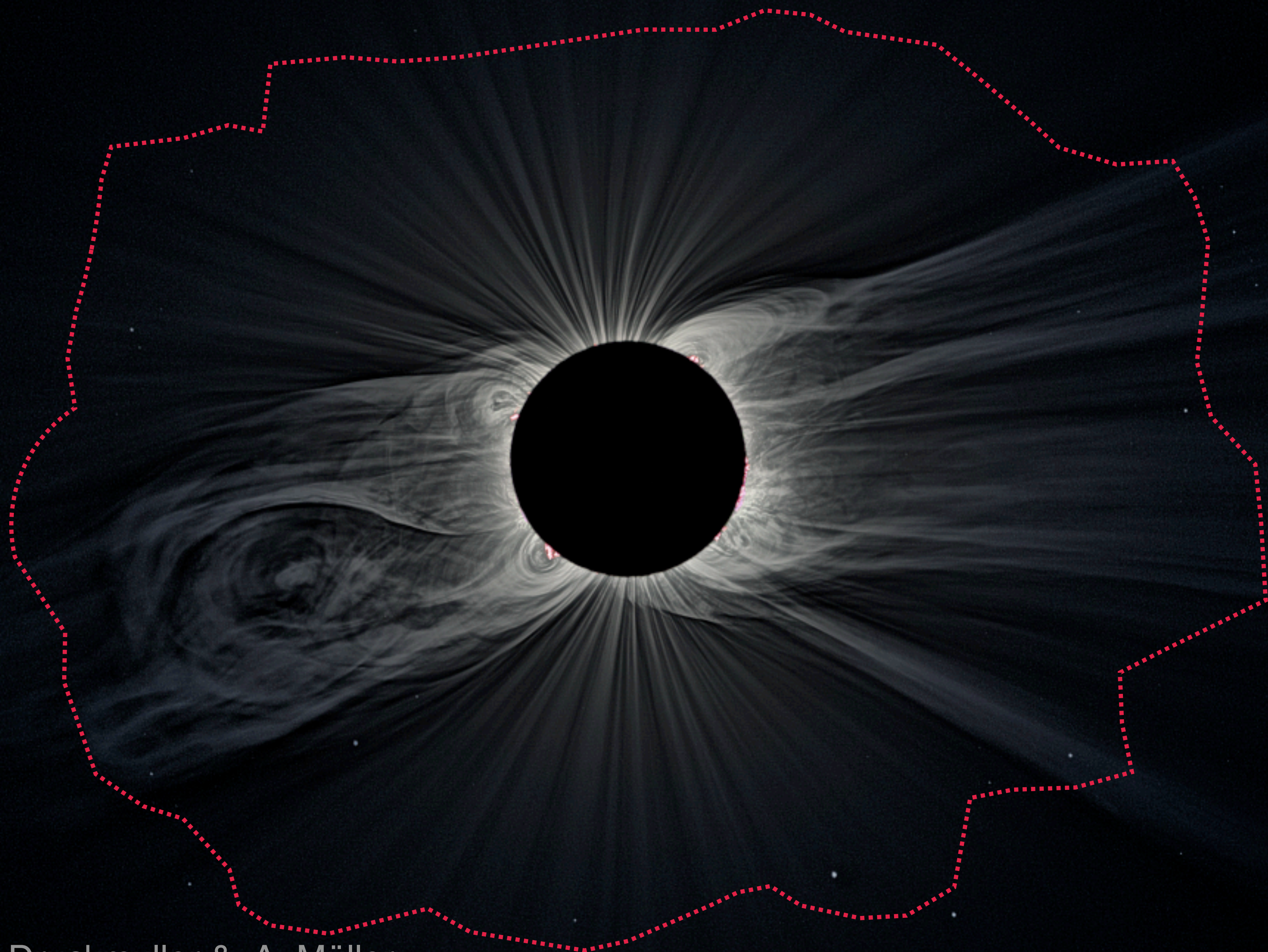


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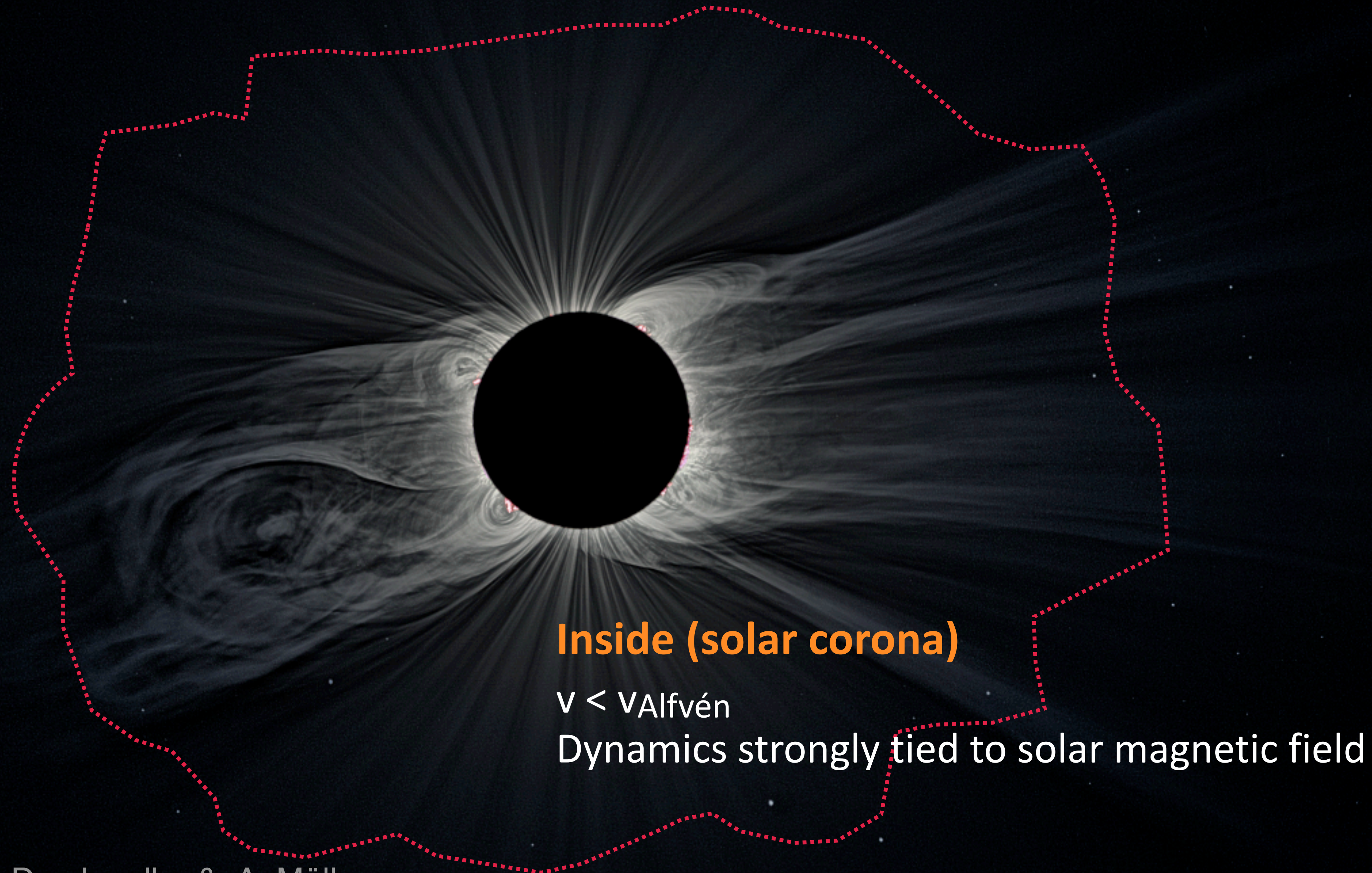
# A symbolic frontier : the Alfvén surface



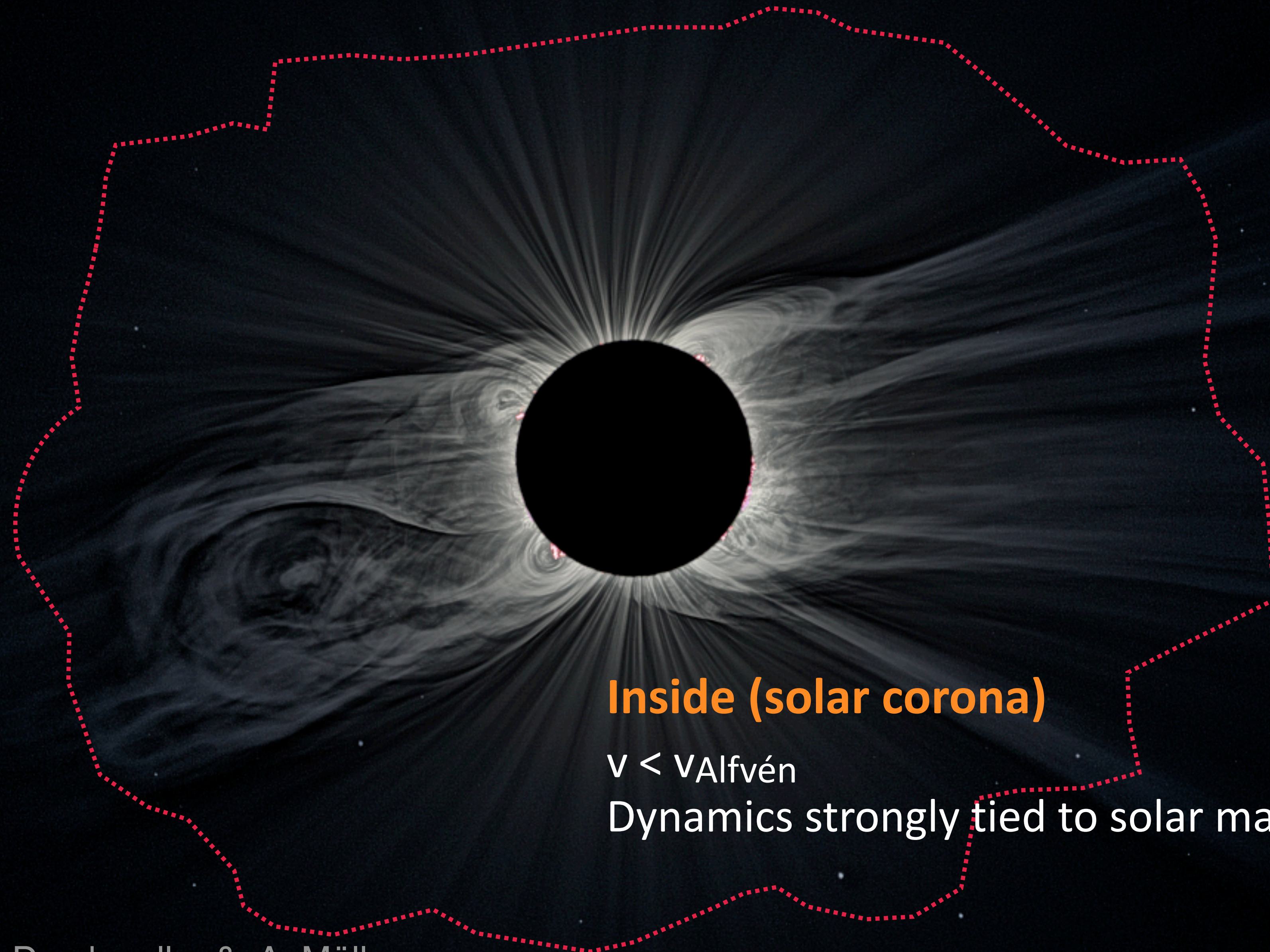
# A symbolic frontier : the Alfvén surface



# A symbolic frontier : the Alfvén surface



# A symbolic frontier : the Alfvén surface



## Outside (solar wind)

$$v > v_{\text{Alfvén}}$$

Magnetic field decoupled  
from the Sun

## Inside (solar corona)

$$v < v_{\text{Alfvén}}$$

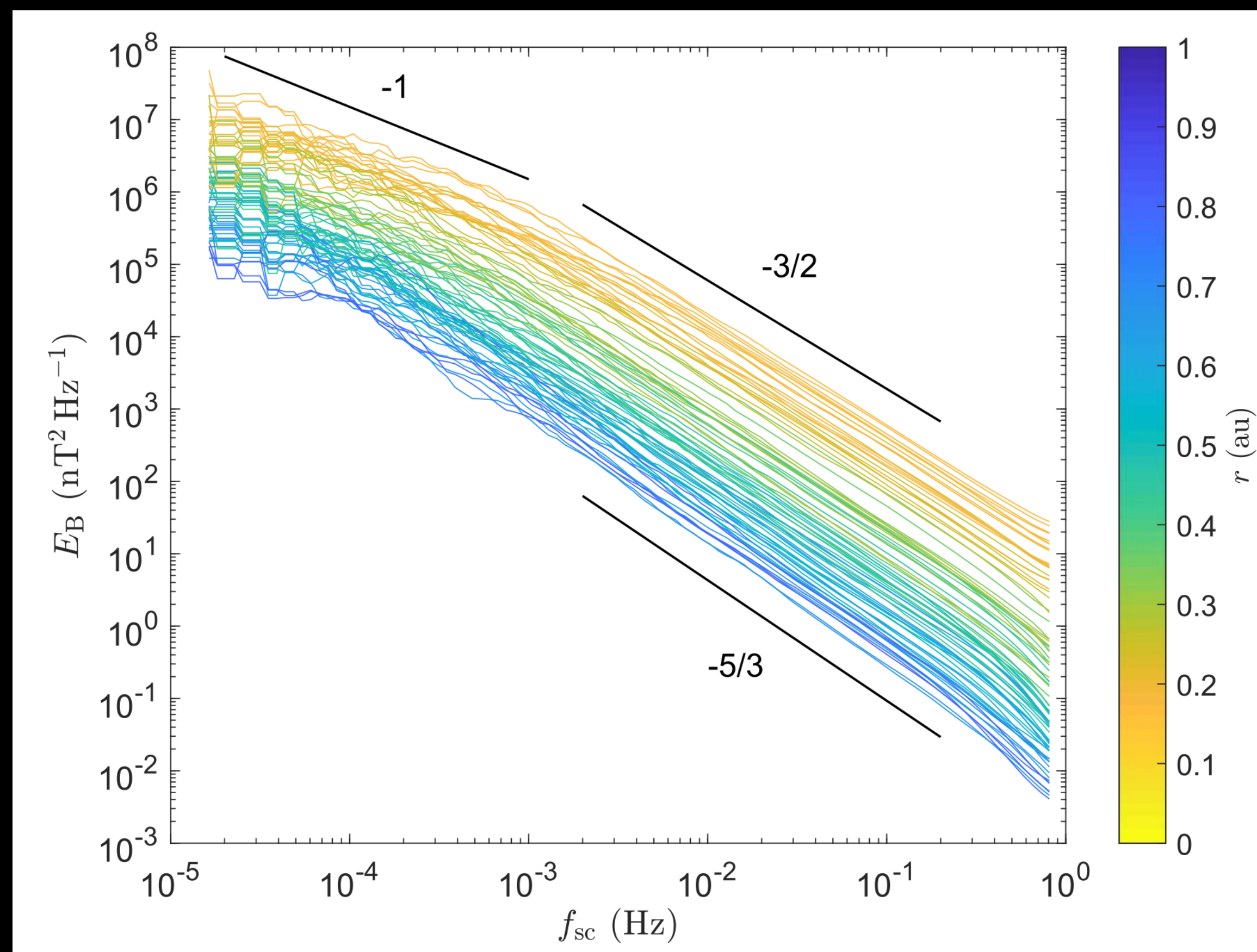
Dynamics strongly tied to solar magnetic field



# Spectrum of solar wind turbulence

- Spectral shape of solar wind turbulence evolves radially :  
from Kraichnan (MHD) to Kolmogorov (hydrodynamic)

Power spectral density  
of magnetic field  
fluctuations



far from the Sun

close to the Sun

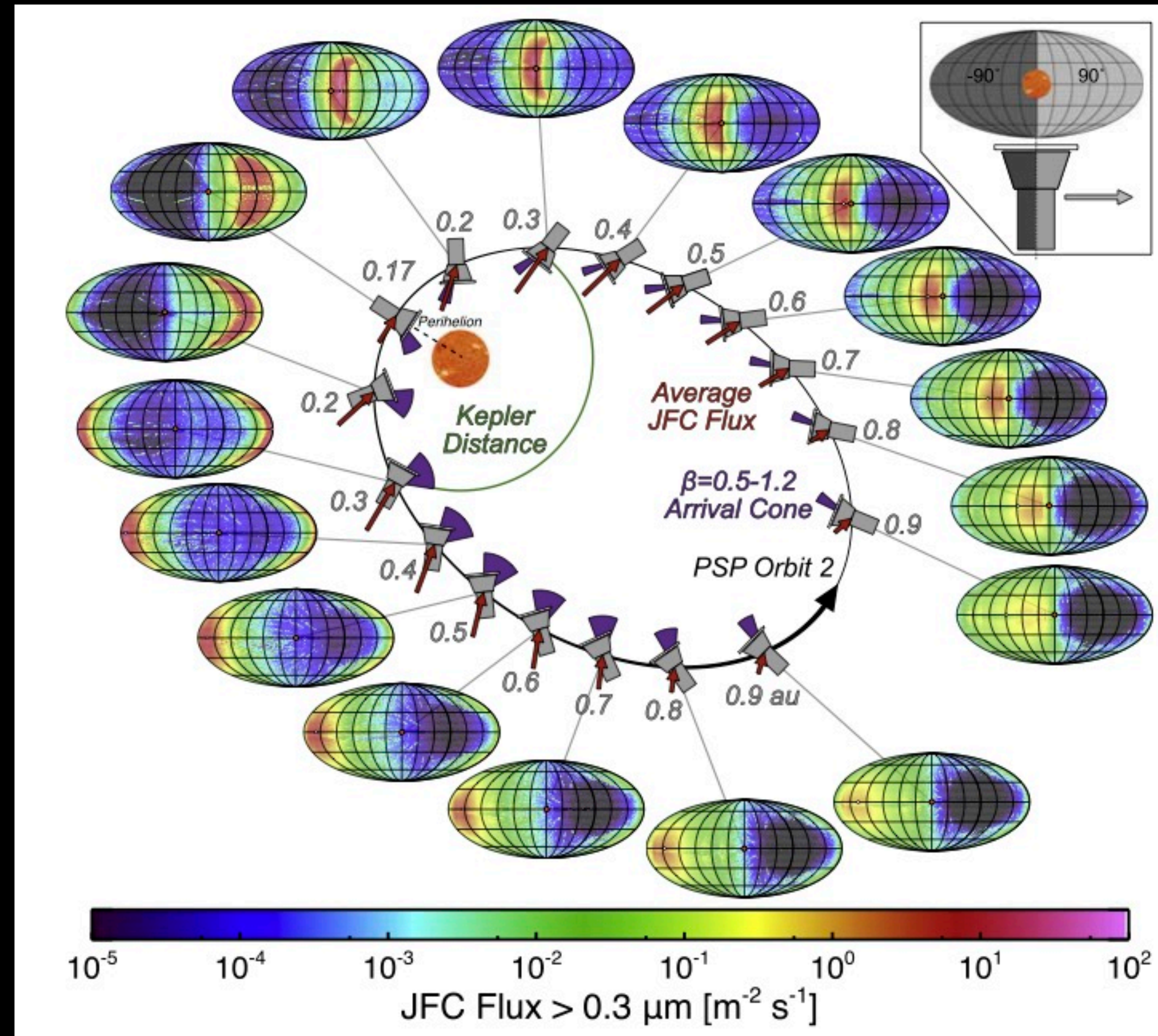
*Chen et al. (2020)*



# Dust impacts

- Large concentrations of dust ( $\beta$  meteoroids, 0.1-10  $\mu\text{m}$ ). Much more variable than expected.
- Dust extinction zone close to the Sun is yet to be observed

Impactor fluxes along orbit #2  
*Szalay et al., 2020*



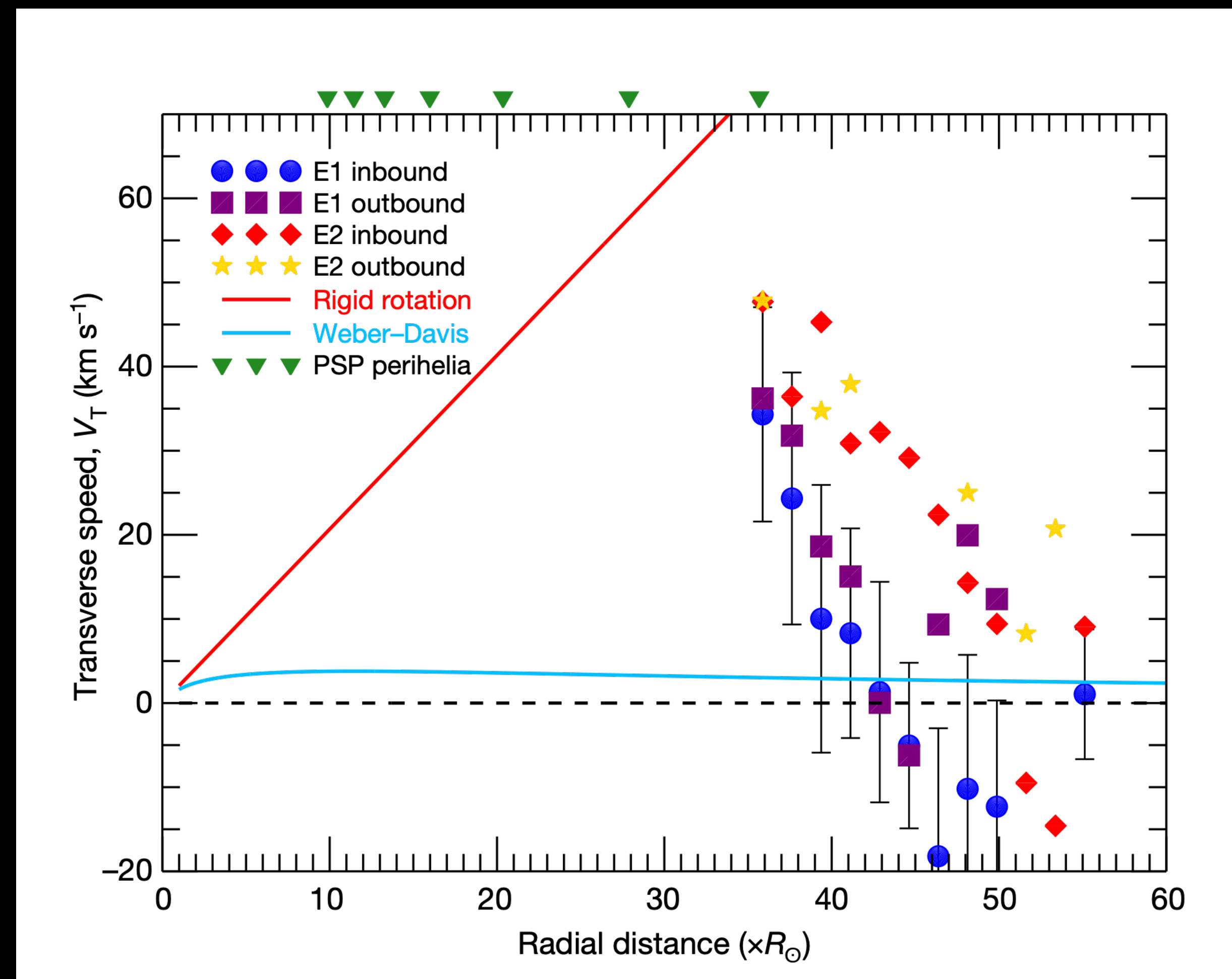
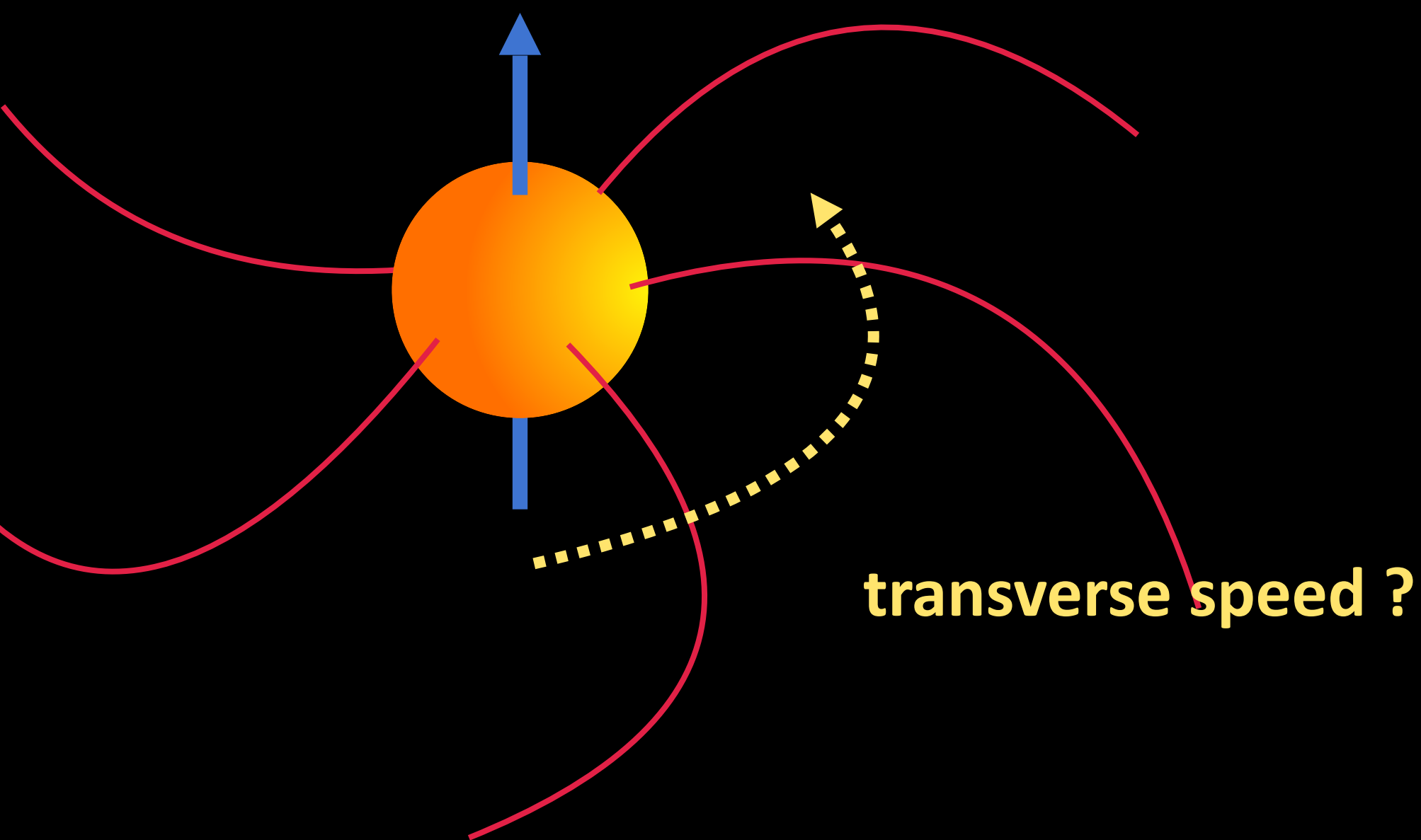




# Anomalous solar wind rotation

*Kasper et al. (2019)*

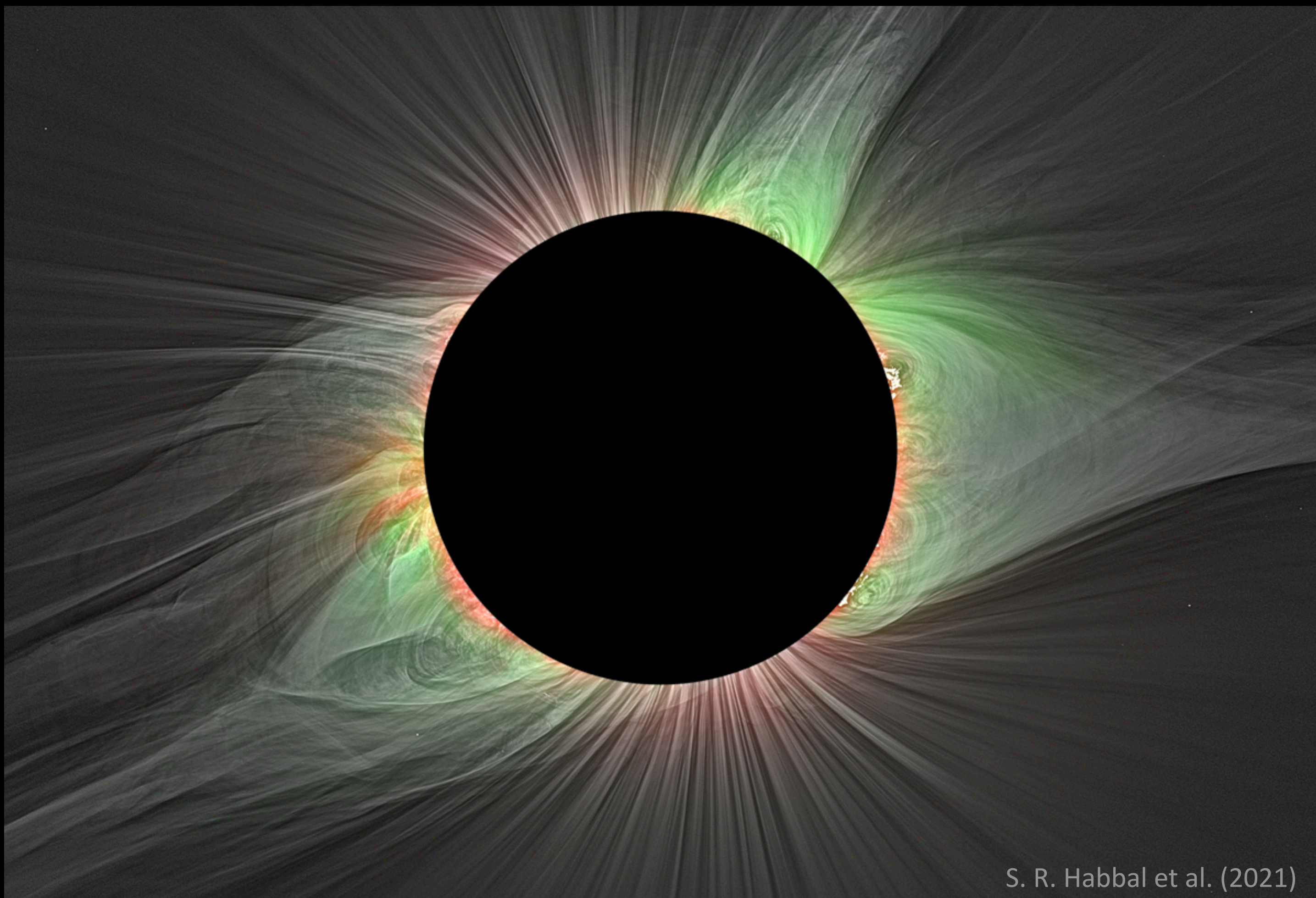
- Rotational flow of the solar wind does not match model predictions
- How does the Sun lose angular momentum and spin down as it ages ?



**To conclude**



# To conclude



S. R. Habbal et al. (2021)

- **Serendipity** : solve one problem and get two new ones for free
- **The future** : we could get as close as  $1 R_{\odot}$  from the surface (instead of  $8.8 R_{\odot}$ ). Will we ?

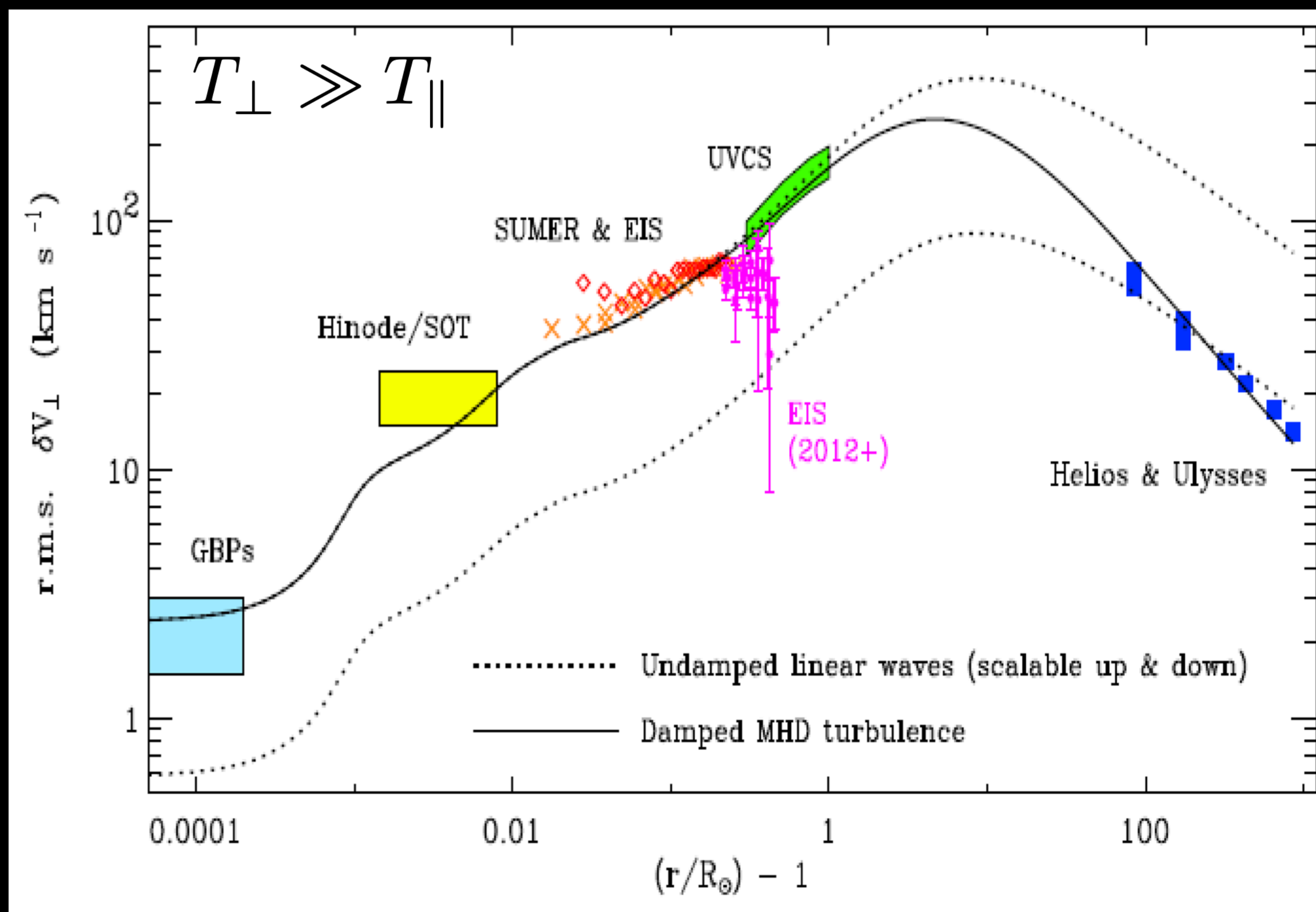




# Candidates for coronal heating

- Heavy ions are preferentially heated → MHD waves are the key to our understanding

velocity fluctuation amplitude



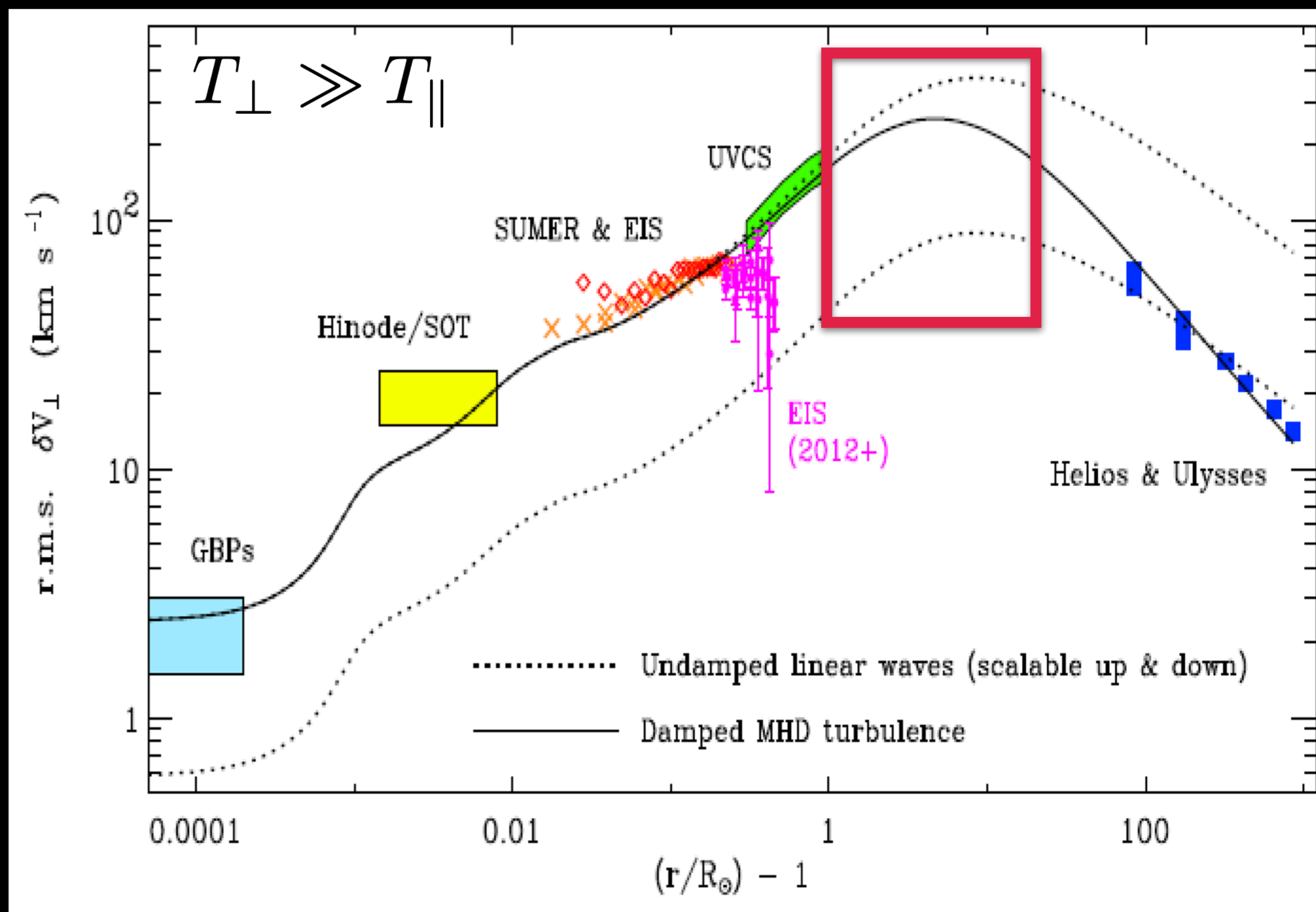
Marsch (2018)



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height above photosphere

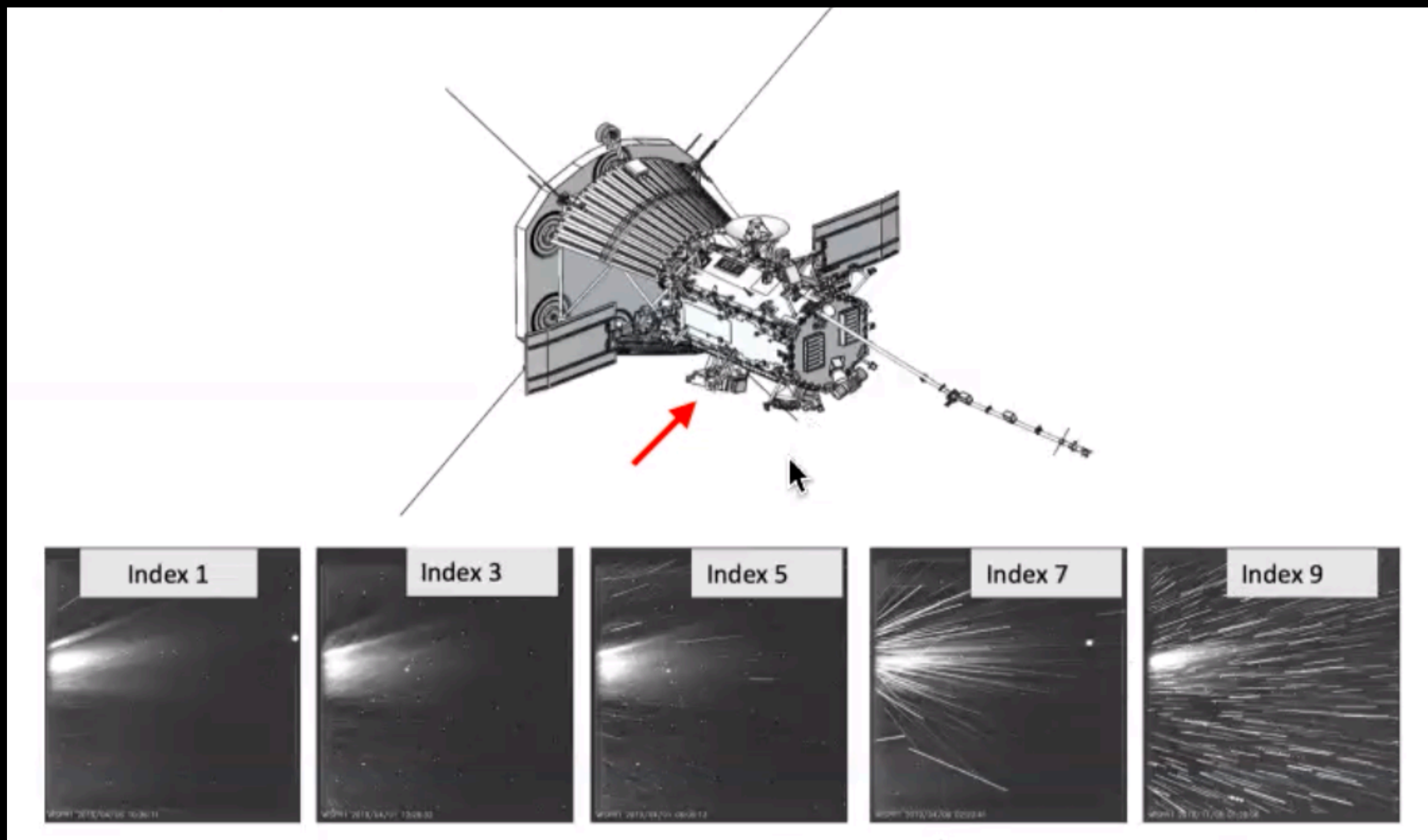
We must probe the solar corona around  $10 R_{\odot}$  to understand what is going on

Marsch (2018)



# Dust impacts

- Impacts by large dust particles generate clouds of debris around the spacecraft



Howard et al. (2020)



# Renaming

Solar Probe Plus gets renamed as **Parker Solar Probe** in honour of *Eugene Parker* (90 yrs old)

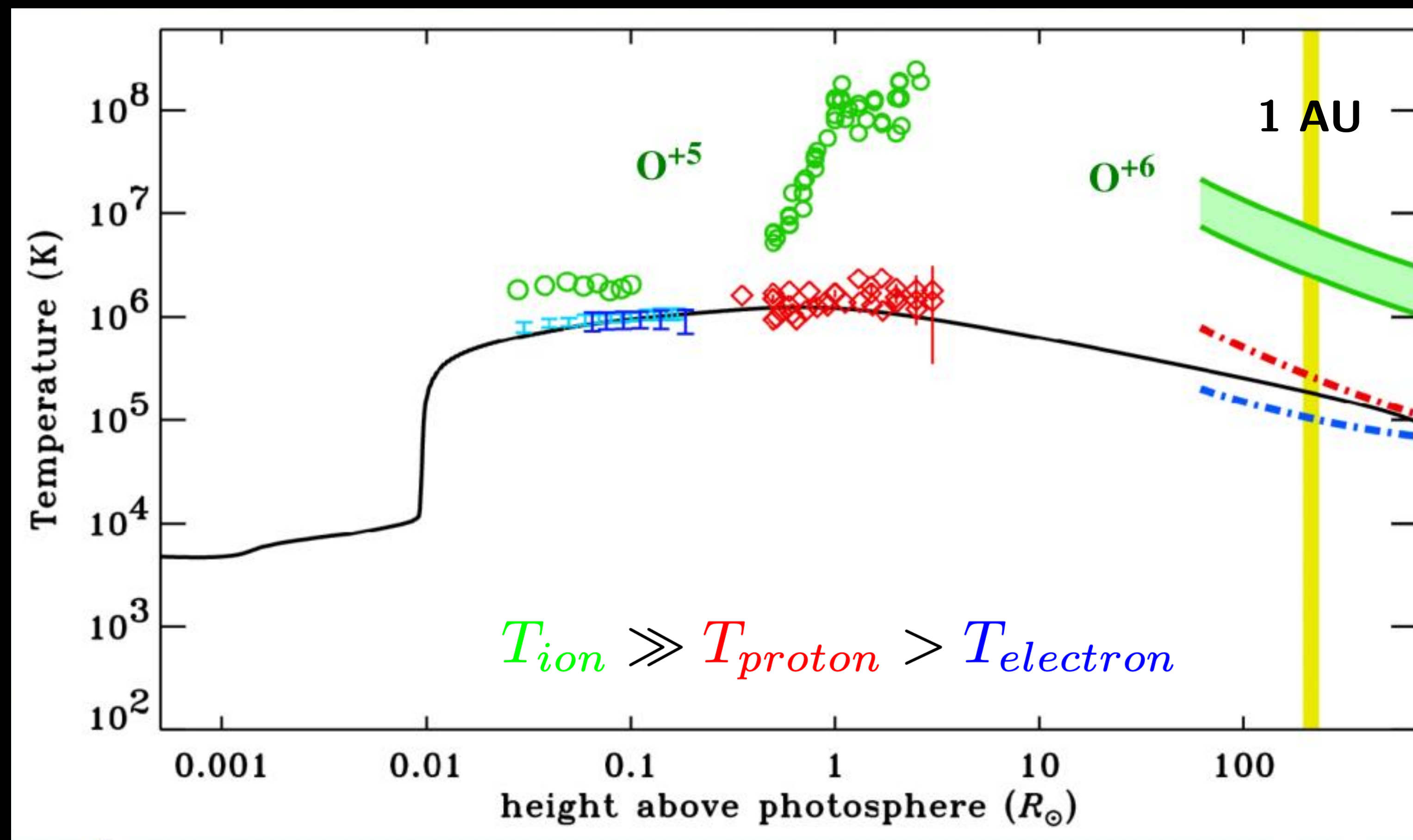






# Where does coronal heating occur ?

- Coronal heating is truly multi-fluid and collisionless



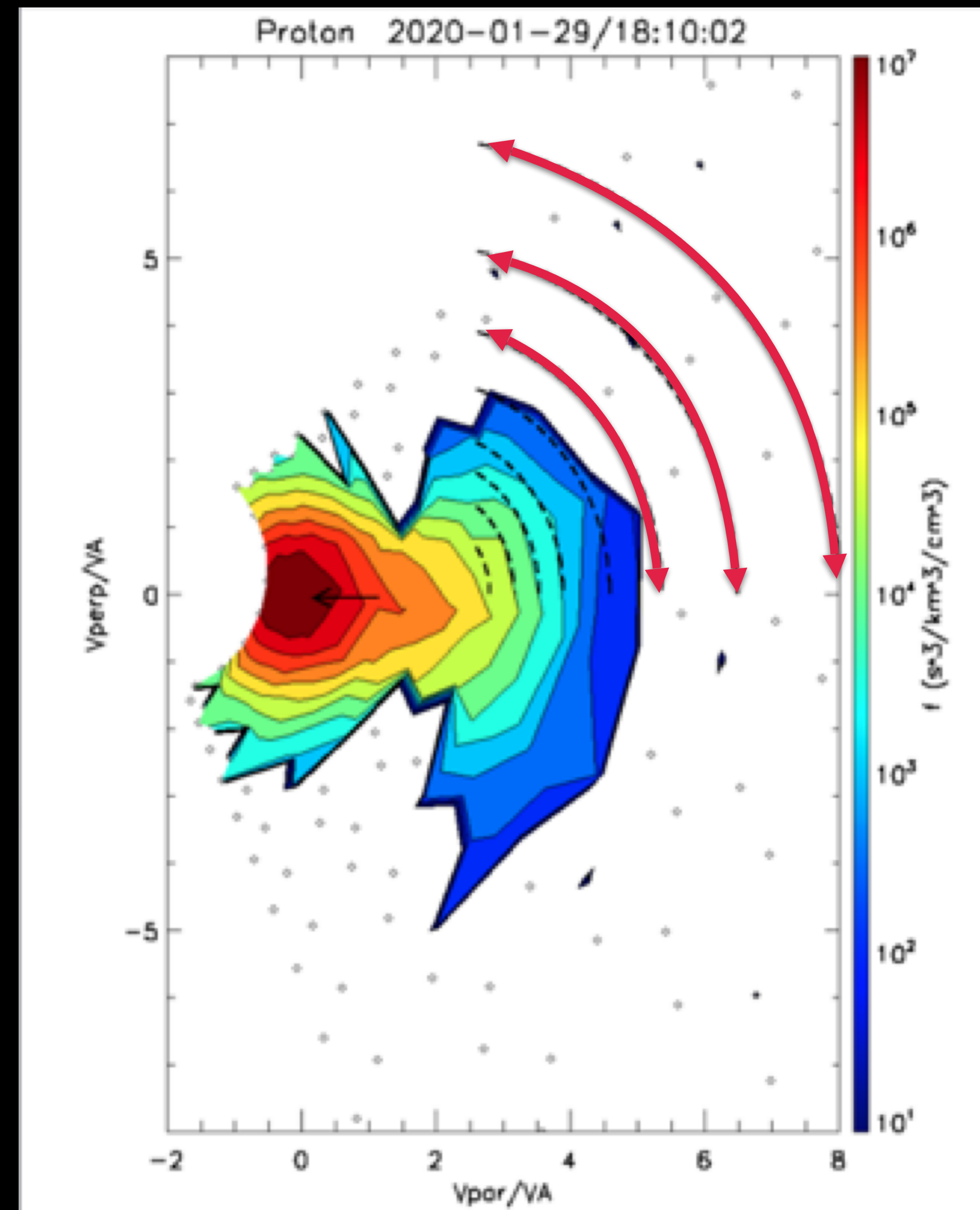
Cranmer (2011)



# Particle velocity distribution

Thermal proton velocity distributions in the solar wind carry the signature of linear wave instabilities

$v_{\perp}$

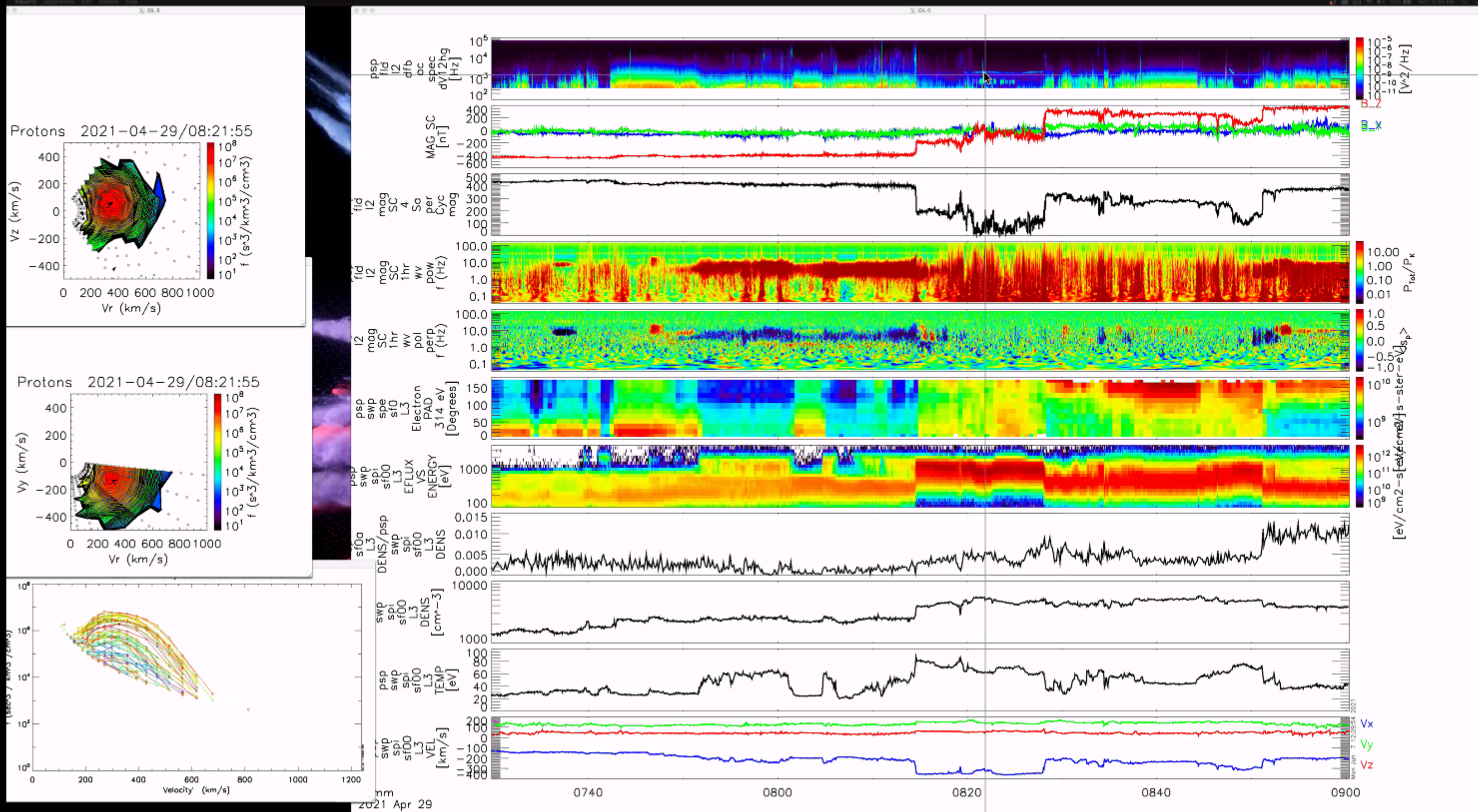


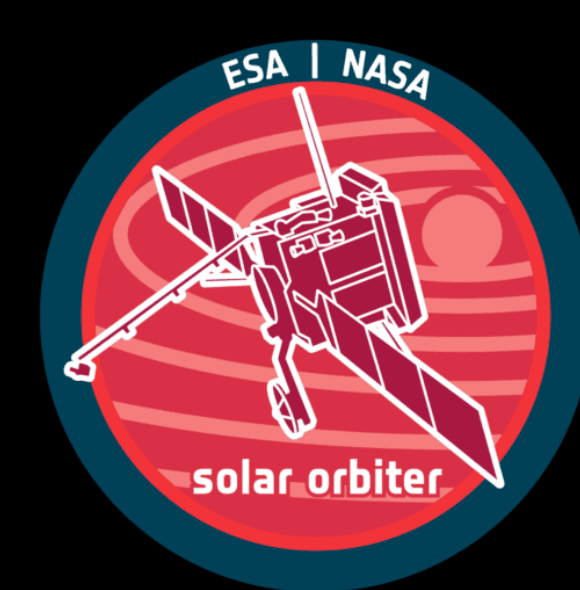
$v_{\parallel}$

*Verniero et al. (2020)*



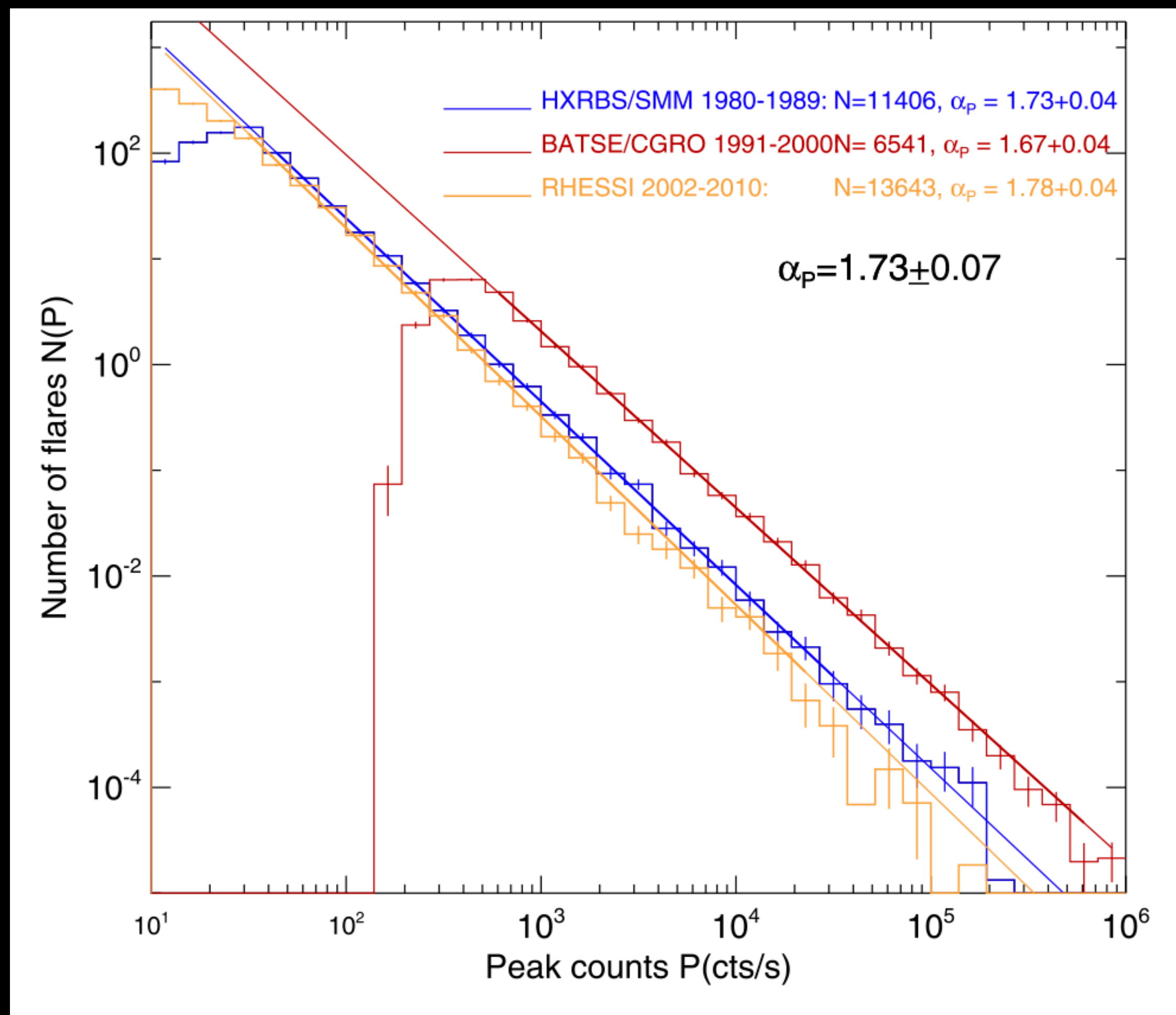
# Piecing it all together





# Self-similarity : small events do matter

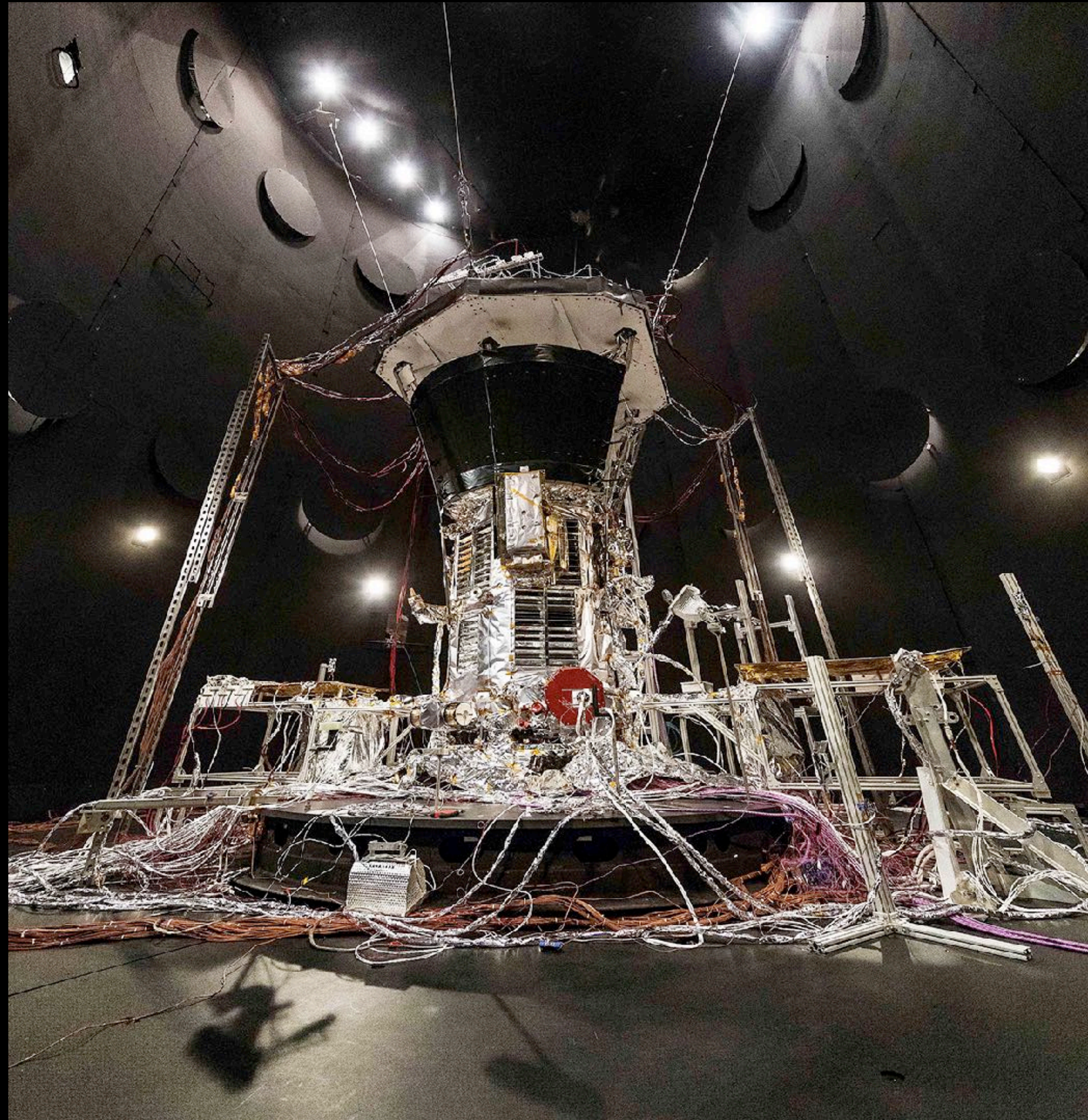
- Frequency distribution of solar flares vs their energy release : power laws galore !



Aschwanden [2014]



# Thermal testing: $-150^{\circ}\text{C}$ to $1800^{\circ}\text{C}$



Odeillo facility (Pyrénées)